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Electrostatic Effects in Fabric Filtration: Volume I. Fields, Fabrics, and Particles. (Annotated Data)

Carnegie-Mellon Univ, Pittsburgh, PA

Prepared for

Industrial Environmental Research Lab, Research Triangle Park, NC

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Filtration	Particulates	
Fabrics	Fabric Filtration	11E
Electrostatics	Particle Charge	20C
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U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Research and Development
Washington, DC 20460

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ABSTRACT

Volume I examines the effect of particle charge and electric fields on the filtration of dust by fabrics. Both frictional charging and charging by corona are studied. Charged particles and an electric field driving particles toward the fabric can greatly reduce the initial pressure drop and also give some reduction in the steady state pressure drop. Efficiency of collection is also increased. Frictional charging is ususally erratic and corona charging limited by dust resistivity. Thus further work is required to develop practical devices.

In long term or equilibrium conditions, nodular deposits attached to fibers may be of major importance. These nodular deposits may act like check valves giving a high pressure drop in the forward or filtering directions, and a low pressure drop in the reverse or cleaning direction. Thus these nodules are difficult to remove by reverse air flow. These nodular deposits, as well as electrostatic fields between adjacent fibers of a filter, appear to be electrostatic in nature. This appears to be an important area for further research.

FOREWORD

The United States Environmental Protection Agency (EPA) awarded a research grant to Carnegie-Mellon University for basic work on electrostatic effects in fabric filtration. The research was performed by coinvestigators (E.R. Frederick and G.W. Penney) and is reported in two volumes: one by each investigator.

Because of the exploratory nature of the research a non-standard format was developed for the reports: an annotated data book. The reports describe a series of individual, but related experiments each designed to investigate a specific facet in electrostatics effects. Although major conclusions and recommendations are included at the beginning of each volume, there are separate conclusions following most of the individual experiments. In some cases the experiments were inconclusive, but provided data and discussion for future work.

The authors brought considerable experience to their work and have presented many speculations not conclusively supported by the experimental data. Finding such support should provide the basis for a number of future research projects. It is expected that the data and discussions presented in these two volumes will serve to help initiate such projects as well as to give the fabric filtration community explicit knowledge not previously obtainable.

John K. Burchard
Director
Industrial Environmental Research
Laboratory - RTP

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Section 14 of Volume I was given as paper 77-51.6 at the Toronto meeting of the APCA. It is reproduced by permission of Harold Englund, Editor, Journal of the Air Pollution Control Association.

The project could not have functioned effectively without the dedication and independent contributions of the graduate student Robert Lembach and the technicians Ron Feigel, Kirk Ludington, David Richey, John Wieczorkowski, and Brent van Zandt.

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SECTION 1

INTRODUCTION

The thesis that electrostatics, developing normally in particulate collection by fabric media, are very important in controlling the filtration process has long been espoused by E.R. Frederick.[1] He has been interested particularly in relating the relative triboelectric properties of dusts and fabrics and then utilizing these data with other characteristics to specify filter fabrics for optimal performance. Other investigators have applied fields across the thickness of a filter in order to increase the efficiency of dust collection. Discussions with Frederick stimulated G.W. Penney's interest in possible electrostatic effects. He became interested in the possibility of depositing the dust on the surface of the fabric and depositing this dust in a relatively porous layer or filter cake. In this concept the filter becomes a support for the collected dust and a means for catching any dust that escapes the electrostatic process.

As described in two patents[2,3] dust particles can be deposited in a porous manner on the filter fabric under the following conditions:

1. The particles are electrically charged.

2. There is an electric field driving the charged particles toward the filter surface.

3. The dust and fabric have sufficient conductivity so that the surface is an equipotential.

The porous deposit is obtained because charged particles tend to follow the lines of force of the field. These lines of force tend to concentrate at any projection. Thus the dust deposit is greater at a projection.

Any slight initial projection then tends to grow. In this way dust can be deposited in a fiber like manner.

As described in the patents, the dust is charged by corona. However corona charging requires that resistivity be of the order of 2×10^{10} ohm-cm or less. This is easy to do in the laboratory but it turns out that in most filter applications the resistivity is materially above this 2×10^{10} ohm-cm limit.

---

[1]Edward R. Frederick, "How Dust Filter Selection Depends on Electrostatics," Chem. Engr. 68, 107 (1961).

[2]Gaylord W. Penney, U.S. Patent No. 3,910,779 Electrostatic Dust Filter, October 7, 1975.

[3]Gaylord W. Penney, U.S. Patent No. 3,966,435 Electrostatic Dust Filter, June 23, 1976.

Another possibility exists: namely, that the dust is generated in some process such that the particles are naturally charged. In such a case and with proper dimensions the electric field could be produced by the space charge of the dust itself provided that the dust loading is reasonably constant. This would be particularly attractive since it would not require any auxiliary equipment. A grant from the Environmental Protection Agency was obtained to study this and other possible electrostatic effects.

In this grant, Frederick and Penney are coinvestigators. Penney has been primarily concerned with small scale tests to isolate and evaluate particular electrostatic phenomena which may be of importance in fabric filtration. This work is reported in Volume I. Frederick has employed Bench Scale experimental filtration tests and attempted to use the resulting data, with information from supporting evaluations, to relate electrostatic effects with performance. This work is reported in Volume II.

GENERAL CHARACTER OF THE WORK

There has been much speculation but few quantitative tests regarding electrostatic effects in fabric filtration. Thus our work is mainly exploratory in character. A major part of the work has been to determine the order of magnitude of the effects and develop methods of measurement. Considerable time may be required to develop a test. Then if the effect being studied does not appear to have commercial application only a limited number of tests appear to be economically justified.

Electrostatic effects can be divided into two classes - Class I Effects due to large scale fields acting on charged particles. Particles can be charged either by friction or by corona. The average or net charge can be readily measured. Also approximate measurements can be made of the fraction of the particles that are charged to a given polarity. Electric fields can be produced by potentials applied to electrodes or by the space charge of a cloud of particles predominantly charged to one polarity. These electric fields can be measured. Class II Triboelectric Effects: whenever two surfaces having different work functions come in contact, there tends to be an exchange of charge between the two surfaces so that one becomes positive and the other negative. A common example is the rubbing together of two dielectrics.

Triboelectric effects are notoriously erratic because the exchange of charge depends on the difference in work functions of the two surfaces in contact. The work function of a surface depends on surface layers of adsorbed molecules as well as the base material. Two sides of a crystal will in general have different work functions. Thus with crystalline particles it is possible for two identical particles to approach so that opposite crystal faces come in contact. This causes an exchange of charge so that as the particles separate they carry opposite charges.

These triboelectric effects are difficult to control and measure. Static charges are commonly observed with insulators at low humidities where the charges can be retained for long times. However, with particles, low conductivity is not necessary. Kameinski[4] has measured the charging of particles by impingement against surfaces. He has shown that metal particles can be

strongly charged by impingement against a different metal, e.g., tungsten particles were strongly charged when they impinged against a stainless steel target. Thus, with aerosols, triboelectric effects are almost impossible to avoid or eliminate.

The first half of the work under Volume I of the Grant was primarily devoted to Class I effects largely because the parameters could be measured and important effects demonstrated. However as the work progressed it appeared that commercial applications were severely limited by the high resistivity of most industrial dusts. This prevents effective charging by corona. Also it appeared unlikely that many industrial dusts would be found where the particles carried like charges.

Furthermore it appeared that triboelectric effects are very important in fabric filtrations. Nodules of dust appear to be held together and to fibers by electrostatic forces. Also individual particles seem to be held together and to fibers by electrostatic forces. Thus as the work progressed more work was directed to these Class II, or triboelectric, effects. However, the tests are more difficult because the effects are difficult to measure. Two sides of a 1 μm particle may have quite different work functions and as yet there are no satisfactory methods for measuring the work functions of these small areas.

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[4]P. Kameinski, "Triboelectrification of Aerosol Particles by Impingement," Ph.D. Thesis, University of Minnesota (1974).

SECTION 2

SUMMARY

EFFECTS OF ELECTRIC FIELDS ON CHARGED PARTICLES

The combination of charged particles and electric fields can both reduce the pressure and increase the efficiency of a fabric filter. In the laboratory particles can be charged by friction or by a corona discharge. If then an electric field is provided to drive particles toward the fabric, the particles are deposited primarily on the fabric rather than in the fabric. Furthermore, the dust deposit for filter cake tends to be of a porous nature, giving a low pressure drop.

In one form, silica particles are blown against a tungsten carbide target, giving the particles a negative charge. If then this charged aerosol is blown inside of a filter bag, the space charge due to the charge on particles gives an electric field driving particles towards the bag.

In another form particles are charged by passing the aerosol through a corona discharge. With either form of charging, the field can be provided either by space charge or by electrodes connected to some voltage source.

In laboratory tests under favorable conditions a marked reduction in pressure drop has been obtained by this method. In our tests an electrostatic (ES) filter and a nonelectrostatic (NES) filter have been operated simultaneously to compare the two methods of operation. The greatest reduction in pressure drop in the ES filter occurs in the first cycle of operation. The filters were cleaned by pulses of reverse air. After many cycles of operation the pressure drop gradually increases, however, the ES filter maintaines a distinctly lower pressure drop than the NES filter.

This combination of charged particles and electric field can increase efficiency as well as reduce pressure drop. Even some relatively porous, woven fabrics in the new or clean condition would give 99% efficiency in the removal of submicron particles in the ES mode as compared to 80% efficiency in the NES or usual mode of operation.

While a decrease in pressure drop and increase in efficiency can be obtained in the laboratory, they cannot as yet be obtained in most industrial situations. Friction charging of the dust is usually erratic and satisfactory corona charging requires that the dust have a resistivity of 2×10^{10} Ω cm or less, but most dust under industrial conditions will have a resistivity of 10^{11} Ω cm or more. Furthermore, even if the dust can be charged, there is another limit of the order of 10^{14} Ω cm above which conductivity of the collected dust cannot carry away the charge on the arriving dust.

EFFECTS DUE TO THE SEPARATION OF CHARGE BETWEEN CONTACTING PARTICLES

It was found that in operating filters the pressure drop in the forward or filtering direction may be several times the pressure drop in the reverse or cleaning direction. This can be traced to dust formations or "nodules" attached to fibers in such a way that they can move relative to the fabric and thus act as crude check valves. These nodules appear to be held together by electrostatic forces associated with differences of work functions or contact potentials. It appears that this type of electrostatic force between adjacent particles may be very inportant in the normal operation of filters. Such forces may be responsible for dust formations which are difficult to remove from filters.

CONCLUSIONS

In the laboratory where the resistivity of dust can be decreased by raising the relative humidity, electrostatic forces can materially reduce pressure drop and increase efficiency of fabric filters. However, more work is required to accomplish this in typical industrial situations.

Electrostatic forces between adjacent surfaces appear to be important in holding particles to each other and to fibers. This appears to be an important area for fundamental studies.

SECTION 3

FRICTIONAL CHARGING OF DUST

BACKGROUND

As discussed in U.S. Patents 3,910,77 and 3,966,435, a porous dust deposit can be produced by charged dust particles in the presence of an electric field driving these particles toward the filter surface. Electric fields are usually produced by electrodes at high potential. However, fields can also be produced by the space charge of the particles themselves. As will be discussed, the dust particles must have charges of like sign and there must be the proper relationship between dust density and filter dimensions. If then the dust could be properly charged by friction, the porous dust deposit could be obtained with all filter surfaces at ground potential and without requiring any high voltage sources or electrodes. The high potentials would be produced by the dust itself.

According to the triboelectric series viewpoint, if particles from one end of the series rub against a material from the other end of the triboelectric series all particles should carry electrical charges of the same sign. Experiments with friction charging of materials such as fabrics suggests that a vigorous rubbing should give the strongest charge.

This suggests that, if particles can be made to rub vigorously against a material of widely different triboelectric properties, all particles should be charged to the same polarity.

PURPOSE

The primary purpose of the test was to obtain an aerosol in which all particles had strong charges of the same sign. This charged aerosol could then be used for filter tests. Another purpose was to obtain information on the frictional charging of dust as an aid in locating industrial situations in which the particles might carry unipolar charges.

FIRST APPARATUS FOR CHARGING DUST

It was first assumed that a large amount of rubbing of a particle against a surface would produce the maximum charge. So the first apparatus consisted of a vortex chamber into which particles could be injected and, by centrifugal force, be thrown to the outside where they would rub against the chamber wall or liner. The liner of the vortex chamber could be changed to test the effect of triboelectrically different materials.

A sketch of the vortex chamber is shown in Figure 1 and a diagramatic sketch of the assembled apparatus is shown in Figure 2.

TEST RESULTS

The measurements of dust coming out of this vortex chamber seemed to be completely erratic. The average charge was small and variable. Various linings and dust were tried as well as means for feeding dust into the cylinder but no consistent readings were obtained.

Methods for measuring positively and negatively charged fractions of the dust will be discussed later, but the conclusion was the dust leaving the vortex chamber was a mixture of positively and negatively charged dust regardless of the positions in a triboelectric series of the dust and vortex chamber liner.

CONCLUDING OBSERVATION

The liner of the vortex chamber usually developed holes due to abrasion. With a copper liner silica dust coming out of the chamber seemed to have a slight copper color. Thus it might be that the particles were being contaminated by materials worn off from the vortex liner.

CONCLUSION

Instead of intensive rubbing we should try a single impingement of particles against a target. The target should be a hard material to minimize wear. This leads to the impingement charging apparatus.

SECOND DEVICE FOR CHARGING DUST

In order for a particle to make a single contact with the target material, dust was blown through a nozzle so that it would impinge against a target. Most dusts have a wide range of particle sizes. In order to insure that the fine particles strike the surface, a high velocity (20,000 ft/min or more) is desirable.* A photograph of the apparatus is shown in Figure 3. A fluidized bed dust feeder is supplied with compressed air at 5 to 15 lbs. pressure. A hose connects this feeder to a nozzle of 1/16" to 1/8" diameter. A tungsten carbide target is mounted with its surface oriented about 45° with respect to the jet. Initially the tungsten carbide target was mounted on insulation and with a lead which could be connected to a Keithley Electrometer.

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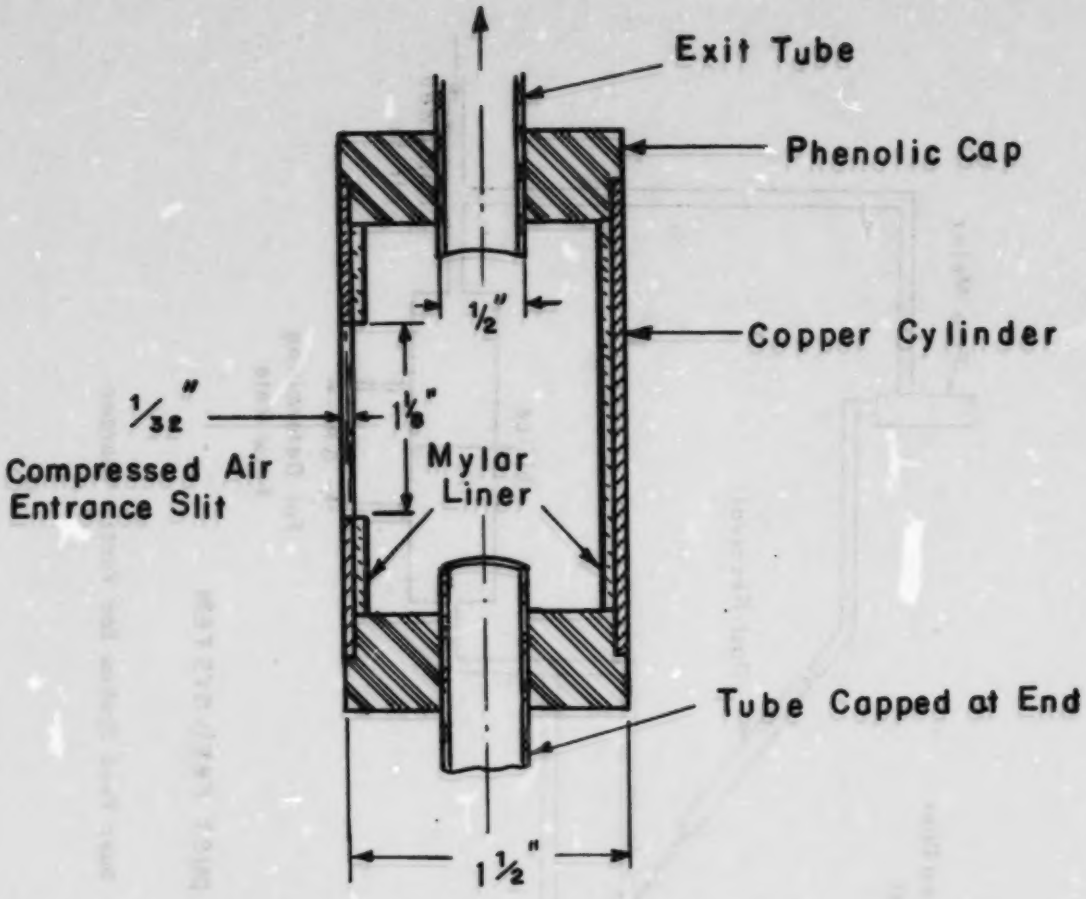
*Our tests attempted to duplicate conditions in industry and so used the units common in industry. Conversion factors for converting to metric units are given in Table 1.

TEST RESULTS

Initially the current to the tungsten carbide target was assumed to be equal and opposite to the charge carried away by the dust. This would be true if the dust was uncharged before touching the target. But it was found that there could be considerable charging of dust in passing through the nozzle. Thus the current to the target was not a true measure of the charge on the dust as it left the target. For this reason the charge on the dust is measured by collecting the dust in a filter and the charge evaluated by the current imparted to the filter.

The results of impinging various dusts against a tungsten carbide target are shown in Table 2. The dusts tested are samples submitted by various filter users. These were merely exploratory tests. With the fly ash, the dust loading and also the charge density were both high, but we did not make tests to determine if the charge was proportional to dust loading. The charge density of 1.75×10^{-4} was about the upper limit that our apparatus was intended to handle. Thus it is possible that this might be space charge limited.



CROSS SECTION OF CHARGER

Fig. 1 - Cross Section of Vortex Chamber for Charging Dust by Friction

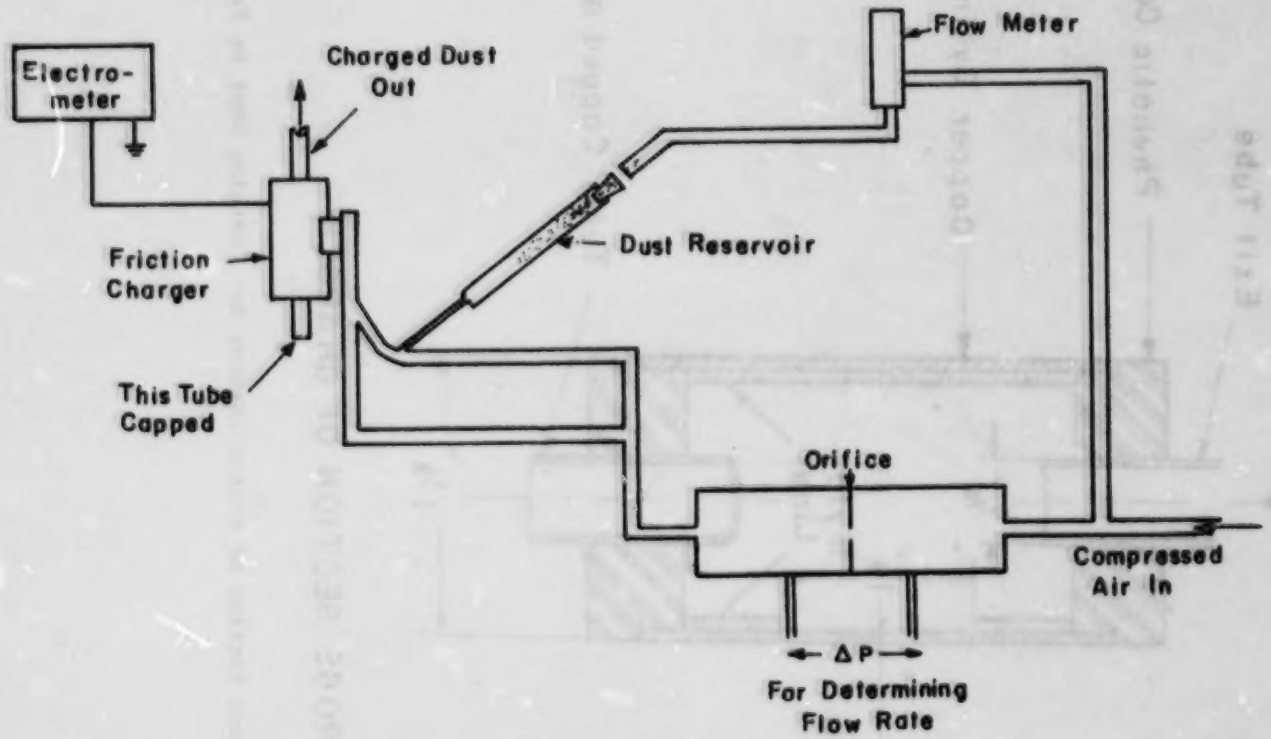


Figure 2 - Dust Feed System for Vortex Charger

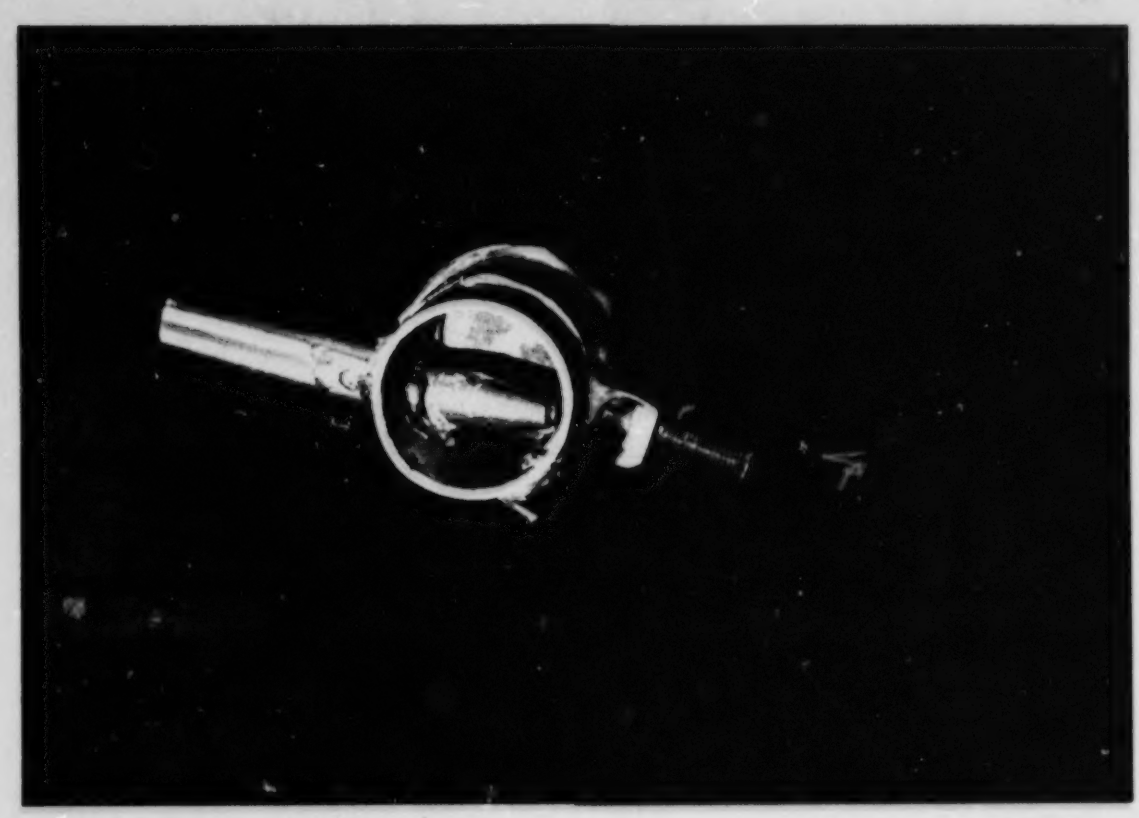


Figure 3 - Photograph of Device for Charging Dust by Impingement

TABLE 1. CONVERSION FACTORS

To Convert From:	To:	Multiply By:
°F	°C	$\frac{5}{9}$ (°F - 32)
ft.	meters	0.305
$ft.^2$	$meters^2$	0.0929
$ft.^3$	$meters^3$	0.0283
ft./min.	meters/sec.	5.08×10^{-3}
$ft.^3$/min. (CFM)	$meters^3$/sec.	4.72×10^{-4}
inches	meters	2.54×10^{-2}
oz.	grams	6.45
grains	grams	0.0647
grains/$ft.^3$	grams/$m.^3$	2.288

TABLE 2. VARIOUS DUSTS CHARGED BY IMPINGEMENT AGAINST A TUNGSTEN-CARBIDE TARGET

Type of Dust	Dust Loading grains/$ft.^3$	Charge Density coulombs/m^3
Electric Furnace Dust, U-P	1.7	$+1.23 \times 10^{-6}$
P.K-Pico Resin	19.6	$<1.7 \times 10^{-9}$
Ferromolybdenum	3.4	-1.58×10^{-6}
Fly Ash	32.0	-1.75×10^{-4}
Potato Dust	6.2	$+1.75$ to $+15.8 \times 10^{-6}$
Acrylic Polymer Dust	6.4	Variable Sign
Molybdenum Dust	3.1	-7×10^{-6}
Rock Dust From Asphalt Plant	3.2	$+1.05 \times 10^{-6}$
Silica	8.5	-3.5×10^{-5}

SECTION 4

POTENTIALS AND FIELDS DUE ELECTRICALLY CHARGED AEROSOLS

Potentials due to an electric charge distributed throughout a volume are given by Poisson's Equation:

$$\nabla^2 V = -\frac{\rho}{\varepsilon_o} \qquad (1)$$

The charge density ρ (coulombs/meter^3) is assumed to be uniform throughout the volume.

$\varepsilon_o = 8.85 \times 10^{-12}$ Farads/meter.

V = Potential (volts) at a point having coordinates x,y,z.

1. Potentials between infinite parallel grounded planes separated by a distance H (meters).

This is a one dimensional problem so the Eq. 1 reduces to:

$$\frac{d^2V}{dx^2} = -\frac{\rho}{\varepsilon_o} \qquad (2)$$

Solving and using the boundary conditions that

V = 0 at x = 0 and at x = H gives:

$$V = +\frac{\rho}{2\varepsilon_o}(Hx - x^2) \qquad (3)$$

The electric field is:

$$\frac{dV}{dx} = \frac{\rho}{2\varepsilon_o}(H - 2x) \qquad (4)$$

2. Field inside a long cylinder of radius R:
Transforming Eq. 1 to cylindrical coordinates and solving gives:

$$\frac{dV}{dr} = -\frac{r\rho}{2\varepsilon_o} \qquad (5)$$

$$\frac{V}{2\varepsilon_o} = \frac{\rho}{4\varepsilon_o}(R^2 - r^2) \qquad (6)$$

where r = radius of a point within the cylinder at which the potential is "v."

EXAMPLE

$\rho = 10^{-5}$ coulombs/m^3. This is a medium charge density in our work. In a cylindrical bag R = 10 cm gives a field at the bag surface of 565 volts/cm. In our work 10^{-4} is a relatively high charge density and in the 10 cm radius bag gives a field of 5650 volts/cm. This is a high field. Thus in bags of reasonalbe size it is possible to obtain fields of the order of 3000 volts/cm which in our tests give good results.

Initially the potential produced between parallel plates or at the center of a long cylinder was ured to measure the charge density.

SECTION 5

MEASUREMENT OF NET CHARGE ON AN AEROSOL

In previous work with atmospheric air two methods were used to measure the net charge carried by the particles in a unit volume of gas.

1. Measure the potential at the center of a long cylindrical grounded tube. From Poisson's equation calculate the charge density required to produce that potential.

2. Pass the charged aerosol through an "Absolute" or "HEPA" filter. The filter collects the particles and their charge. The current to the filter is measured with an electrometer. An absolute filter arranged for measuring charge is shown in Figure 4.

The absolute filter is useful for measuring very dilute aerosols. It does not have the dust holding capacity to handle a high dust loading except for very short periods of time. For this reason, initially the charge on dust was evaluated by measuring the potential in some defined volume. Later it was realized that, for our purposes, the charge collected by a fabric filter could be used to measure the charge on the particles. A fabric filter is mounted on a plastic frame with the fabric supported against a metal screen. The current collected by the screen is measured by an electrometer and the rate of air flow through the filter is measured using a calibrated orifice.

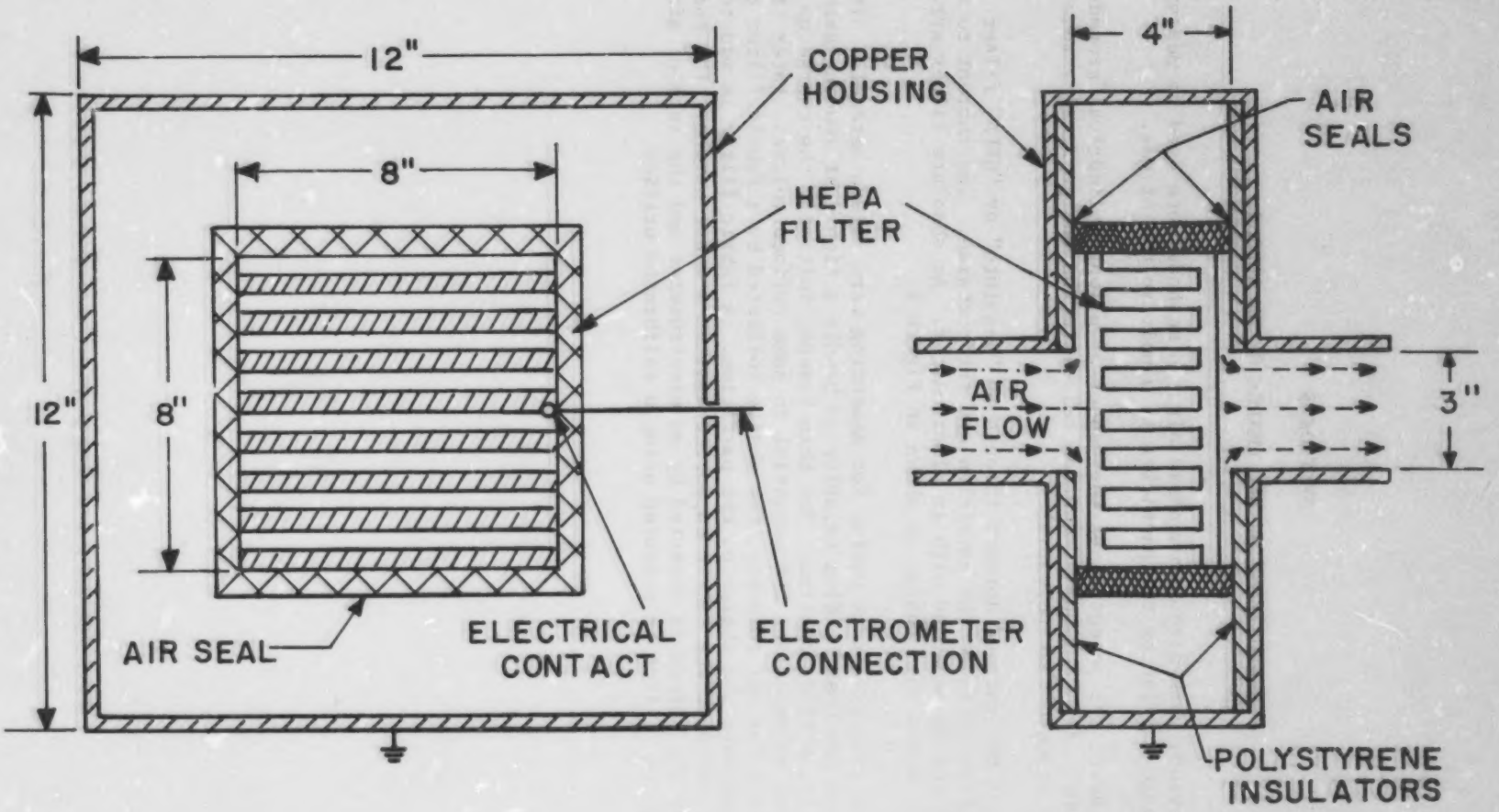


Figure 4 - Cross Sections of Absolute Filter as Mounted for Measuring Net Charge on an Aerosol

SECTION 6

MEASUREMENT OF POSITIVE AND NEGATIVE FRACTIONS

BACKGROUND

As has been mentioned, the measurement of the average or net charge on an aerosol is relatively simple, but the determination of the fraction that is positive and the fraction that is negative is not so simple.

With fine (0.3 μm diam.) oil droplets, the positive and negative fractions can readily be determined by passing the aerosol between positive and negative plates with the aerosol at a velocity of 50 to 300 ft./min. But with our test dusts there are many difficulties.

PURPOSE OF TESTS

These tests attempted to attract negatively charged particles to the positive electrodes and positively charged particles to the negative electrodes and so determine the fraction of the particles charged to a given polarity.

APPARATUS

The first apparatus consisted of the friction or impingement charger followed by a tapered transition section leading to 3 parallel steel plates with plastic side walls. Each plate was 6" wide by 12" long. A potential was applied to the center plate. The outer plates were grounded through a Keithley Electrometer. This apparatus is shown in Figure 5. Alternately a potential could be applied to the outside plates and the current to the center plate measured.

TEST RESULTS

Silica dust was blown against the target using about 5 lb./in.^{2} pressure. A potential of -4.5 KV was applied to the side plates and the current to the center plate measured. The current from the target was $+2 \times 10^{-8}$ amps and from the center plate -2.5×10^{-8}. This would indicate that the dust had some initial negative charge before it hit the target or that there was some bouncing of dust between plates. Visually the dust on the center plate was estimated to be 10 times as great as that on the side plates. Of this 10% on the outer plates there was no way to tell whether it was initially positively charged so that it was deposited on the negative plates or whether it was first precipitated on the positive plate and then changed its charge and hopped to the negative plate. Also some dust may have been deposited by inertia due to the high velocity at which particles left the tungsten carbide target.

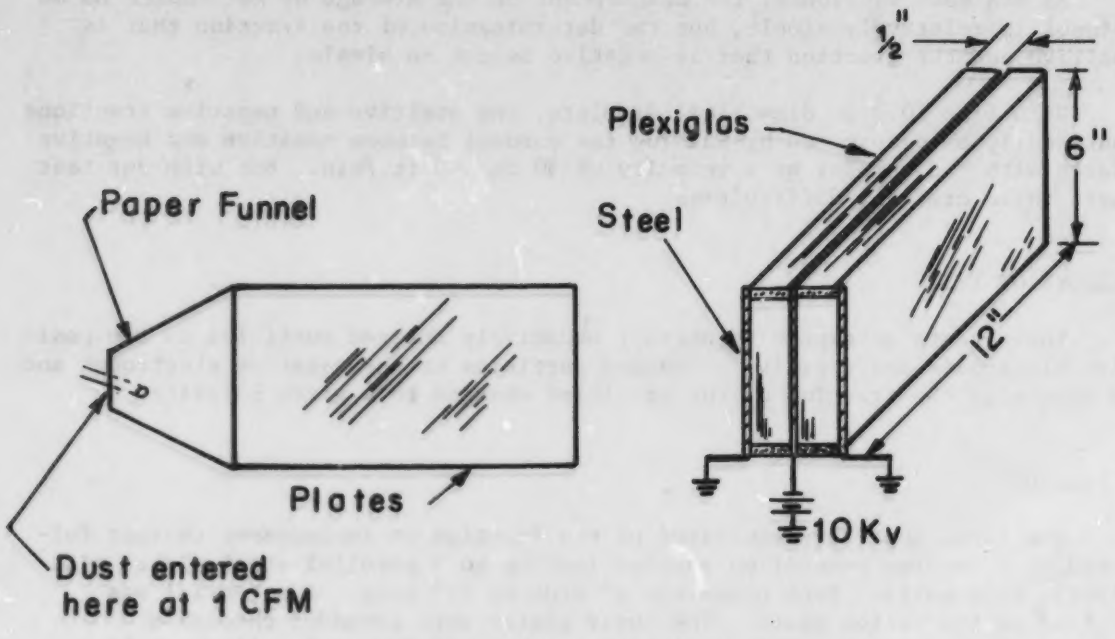


Figure 5 - Parallel Plates for Separating Positive and Negative Fractions of Dust

In these tests some dust was deposited on the cardboard funnel. The measurement of current to the cardboard funnel is illustrated in Figure 6. In a typical measurement the current from the tungsten carbide target was $+4 \times 10^{-7}$ amps and from the cardboard funnel -3×10^{-7} A. This indicates that the high velocity and turbulence in the aerosol leaving the target throws dust against surfaces so that the electric fields are unable to adequately control the motion of the particles.

Other tests were made with varying plate spacings and potentials. However in all cases some of the silica dust would deposit on negative surfaces even though we were attempting to charge this dust negatively.

DISCUSSION

Out test dust contains a wide range of particle sizes. In charging the dust by impingement, a high velocity jet must be used to insure that the fine particles strike the target. The particles leave the target in somewhat random directions. The high velocity air jet causes violent turbulence. Due to the combination of air turbulence and inertial effects, the motion of charged particles can only partially be controlled by the electric field. The tendency of particles to bounce between plates increases with the square of the electric field. This tends to limit the field strength which can be used. Due to these various effects the current to a given plate may not be a true measure of a given polarity of charge in the aerosol. For example a positive plate attracts negative particles but due to inertia and turbulence some positive particles may strike the positive plate.

Thus we do not have any simple means for accurately measuring the fraction of the particles charged to a given polarity. Our judgment is that for the silica dust impinged on the tungsten carbide target between 90% and 100% of the particles are negatively charged.

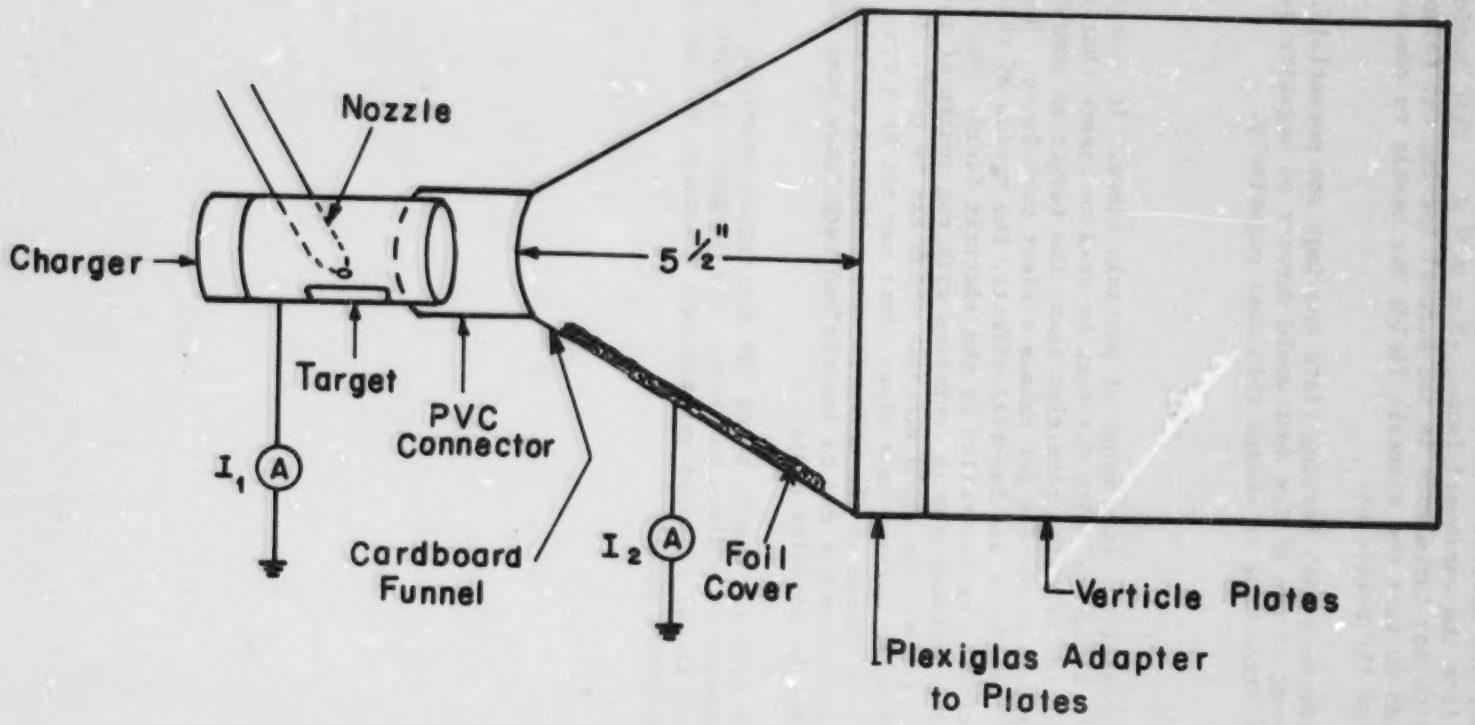


Figure 6 - Foil Electrode Used to Measure Current to Cardboard Funnel

SECTION 7

VISUAL EVALUATION OF ELECTROSTATIC FIELD EFFECTS DUE TO FRICTIONAL CHARGE ON DUST

BACKGROUND

Tests show that dust, particularly silica, blown against a tungsten carbide target acquires a strong electric charge. Theory indicates that a few grains per cubic foot of such charged dust can create strong electric fields tending to drive these charged particles to the containing walls. With a spherical container having a uniform wall, the deposition would be the same for either grounded metal, or an insulating wall. By using a grounded filter with other walls insulated, the field effect can be concentrated at the filter.

PURPOSE

The purpose of this test was to permit a visual inspection of the dust deposit on a filter when dust was charged by friction and when there was a space charge field at the filter surface.

APPARATUS

A flat fabric filter supported against a grounded metal screen was mounted across the face of a rectangular acrylic box. This box formed the outlet or clean air side of the filter. The inlet side of the box was an acrylic box 2" in depth. The filter was 6" x 24". Theoretically much of the dust could be electrostatically precipitated near the entrance. For this reason the outlet box was divided into three sections so that the airflow and pressure drop could be monitored for each of the three sections. The assembled apparatus is shown in the photograph of Figure 7. The chamber containing the impingement charger is shown at the left. The acrylic box was held together by clamps so that it could be readily opened for inspection.

The filterused was polypropylene fabric without antistatic treatment. To evaluate the potential drop through the fabric, there were three metal probes mounted on the face of the fabric. The one at the center was grounded to the screen so that one could observe the electrostatic precipitation of dust at a surface where there could be no filtration. The two probes near the ends of the filter were simply glued to the face of the fabric with an insulated lead going to an electrostatic voltmeter so that the voltage drop through the fabric could be measured.

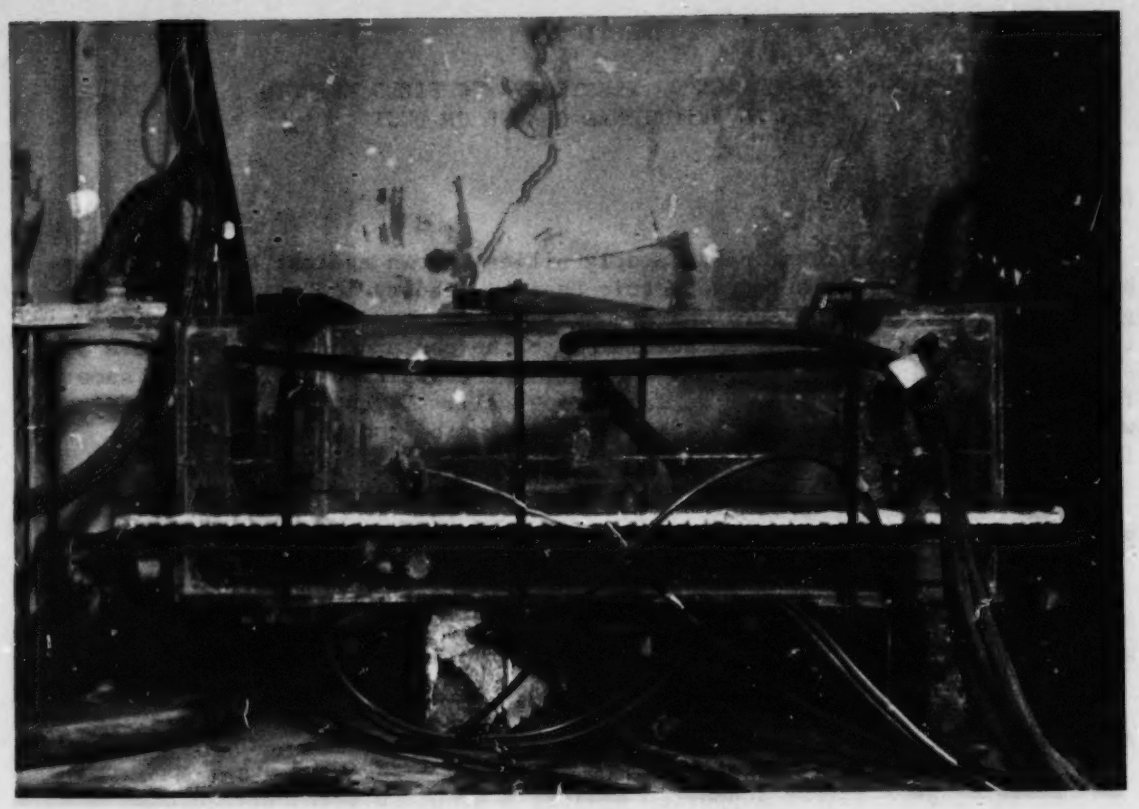


Figure 7 - Photograph of Assembled Filter

RESULTS

After running a short time, the lower box of the filter assembly was removed. A photograph of the lower side of the filter is shown as Figure 8. The heavy deposit on the center grounded probe can be seen at the center of the filter. The two probes near the ends of the fabric operated at about 2000 volts which was the potential drop through the fabric. Thus the potential of the center grounded probe was 2000 volts below the surrounding fabric. This higher field strength at this surface caused a heavy deposit of dust. Close-up photographs of this heavy deposit are shown as Figure 9. In this figure, a rectangular pattern of smaller deposits can be seen at the lower left corner of the photograph. The spacing between these deposits corresponds to the mesh size of the screen supporting the fabric. At each point where wires of the screen cross there is better contact with the fabric; accordingly dust deposited at these positions.

In these tests no difference in the thickness of deposit or pressure drop could be observed along the length of the filter.

In this first test, the fabric had no antistatic treatment and the probes indicated that the potential drop through the fabric was about 2000 volts. In the next test the fabric had an antistatic treatment. The photograph of Figure 10 shows the deposit of dust in this second test. In this case the deposit is distributed over both the fabric and the metal plates. In this case the fibers are relatively conducting and so any projecting fiber collects a dust deposit.

CONCLUSIONS

The electrostatic effects were obtained even though all metal parts (except the two measuring probes) were grounded. The particles were charged by impinging against a grounded surface. The space charge of the cloud of charged dust particles could create strong electrostatic fields tending to drive the charged particles toward grounded surfaces. A strong electrostatic deposition of particles was demonstrated. The electrostatic velocity of the particles relative to the air appeared to be greater than the air velocity through the filter (3 ft./min.).

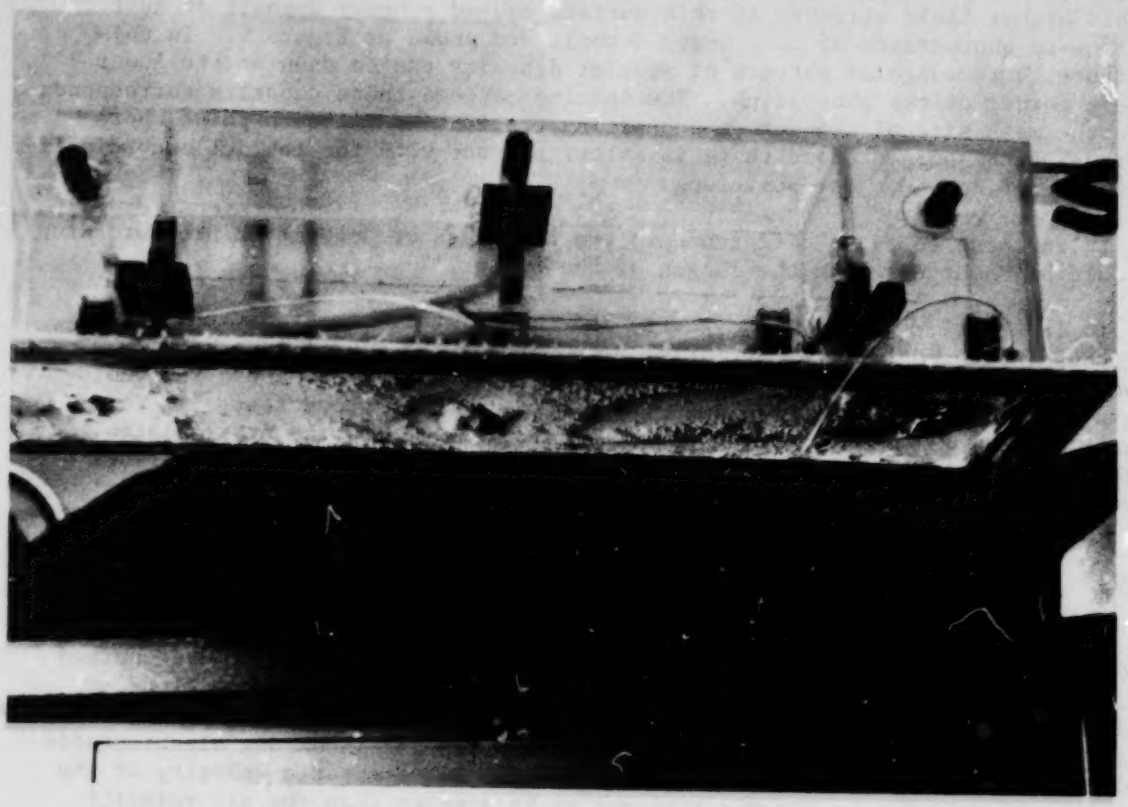


Figure 8 - Photograph With Lower Section Removed
to Expose Uneven Deposit on the Filter

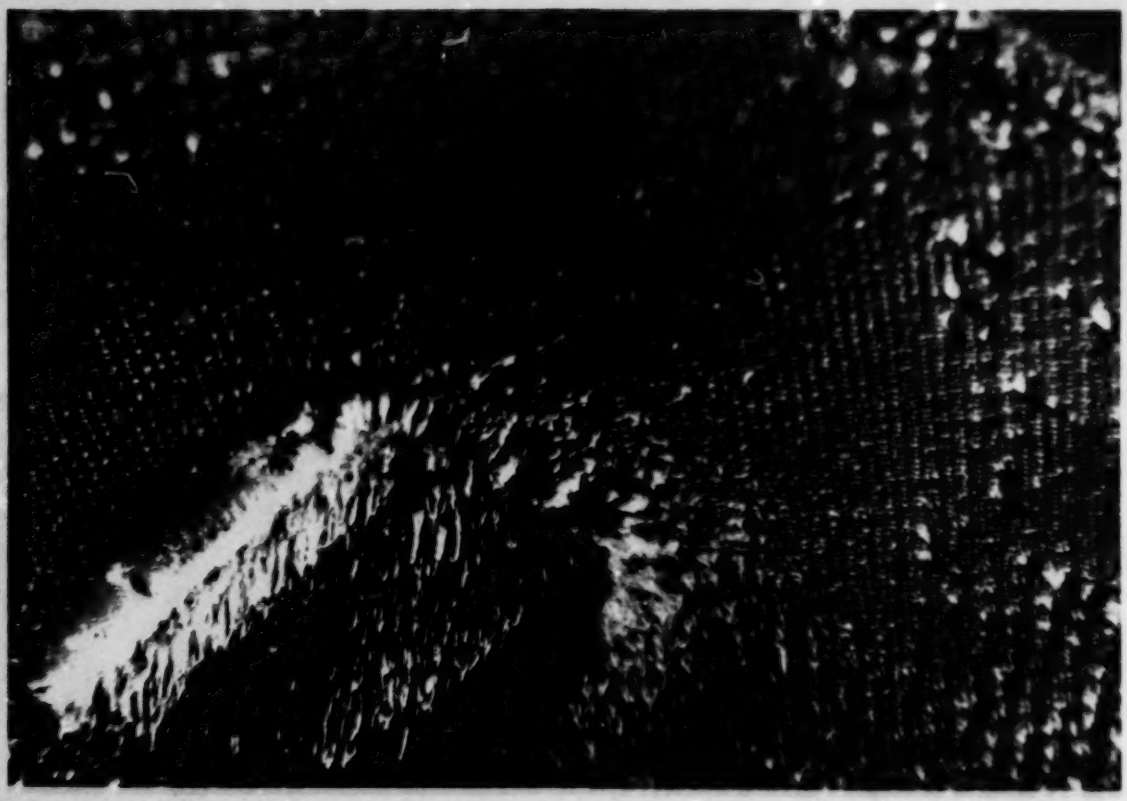


Figure 9 - Close Up View of the Dust Deposit
on a Grounded Metal Plate

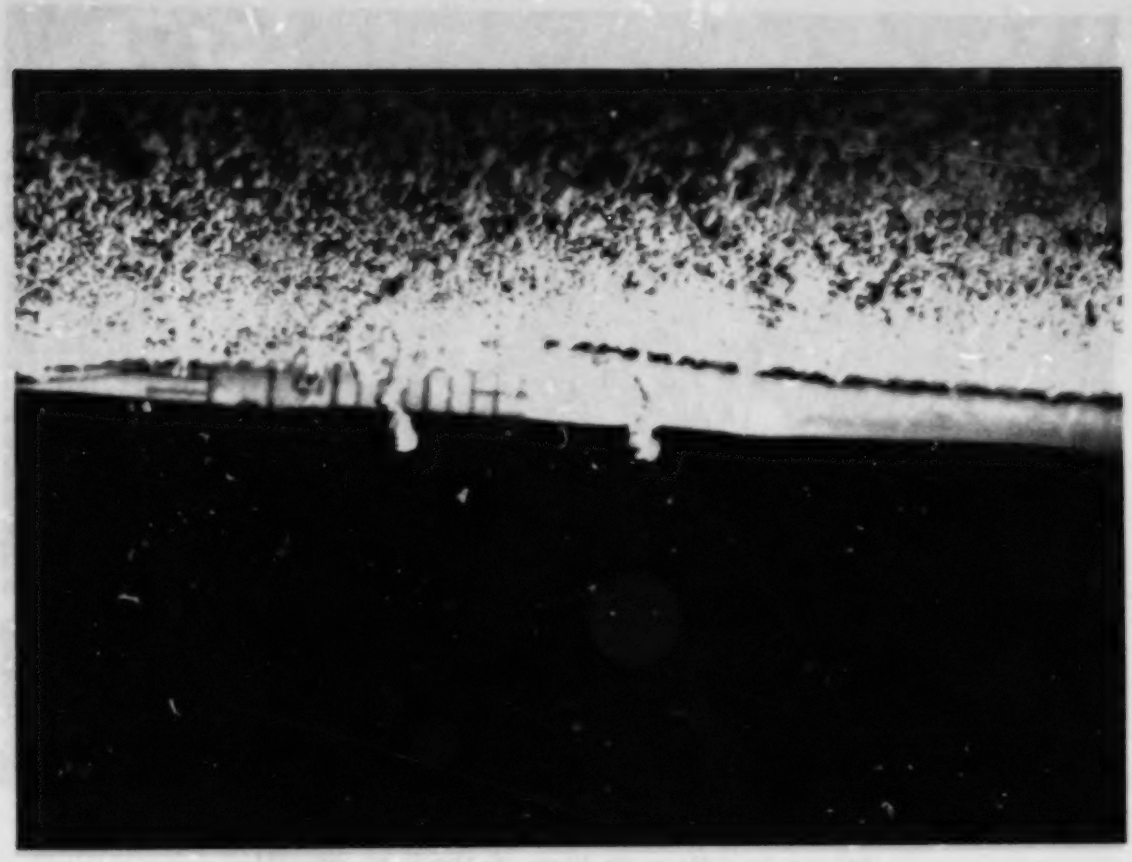


Figure 10 - Photograph of Dust Deposit After a Test in Which the Fabric Had an Antistatic Treatment So That the Filter Surface Was an Equipotential

SECTION 8

PRELIMINARY COMPARISON OF ELECTROSTATIC (ES) AND NON-ELECTROSTATIC (NES) FILTERS

PURPOSE

To study the possibility of reducing the pressure drop of a filter by electrostatic means for situations where the dust is charged by friction and to compare frictional charging and corona charging of dust.

APPARATUS

These tests used the plastic boxes and flat filter used for the visual demonstration. This was shown in Figures 7 and 8. This apparatus used a fabric stretched and glued to a rectangular plastic frame. This frame was then clamped between the two plastic boxes using Mortite as a gasket. At filtering pressures this provides a convenient and effective seal. The fabric was treated with 5% Downy solution which gave a resistivity of about 2×10^9 ohms per square. In order to control the electric field at the fabric surface, a copper plate 6" x 24" was mounted parallel to the filter surface. For the ES tests it was 2" from the fabric with a potential applied to it. For the NES filter, the copper plate was spaced ½" from the fabric and parallel to it.

THE TESTS

Tests were made by first making a test at one condition. The filter was then cleaned using a household vacuum cleaner which appeared to return the fabric to its original condition; then making a test for another condition. Thus three tests were made in series using the same piece of cloth.

The results of one series of tests are plotted in Figure 11. Pressure drop is plotted against running time. For curve #1 there was no impingement of the dust and the grounded copper plate was ½" from the fabric. There is always some charging of a dust in a feeder but for curve #1 the electrostatic effects were a minimum.

For curves 2 and 3 the copper plate was 2" from the fabric with 8 KV applied between the plate and the fabric. The average field was 1.6 KV/cm. although the field at the fabric would be increased due to the space charge of the dust. For curve #2 the dust was charged by impingement and for curve #3 the dust was charged by corona. All tests used pulverized silica as the test dust.

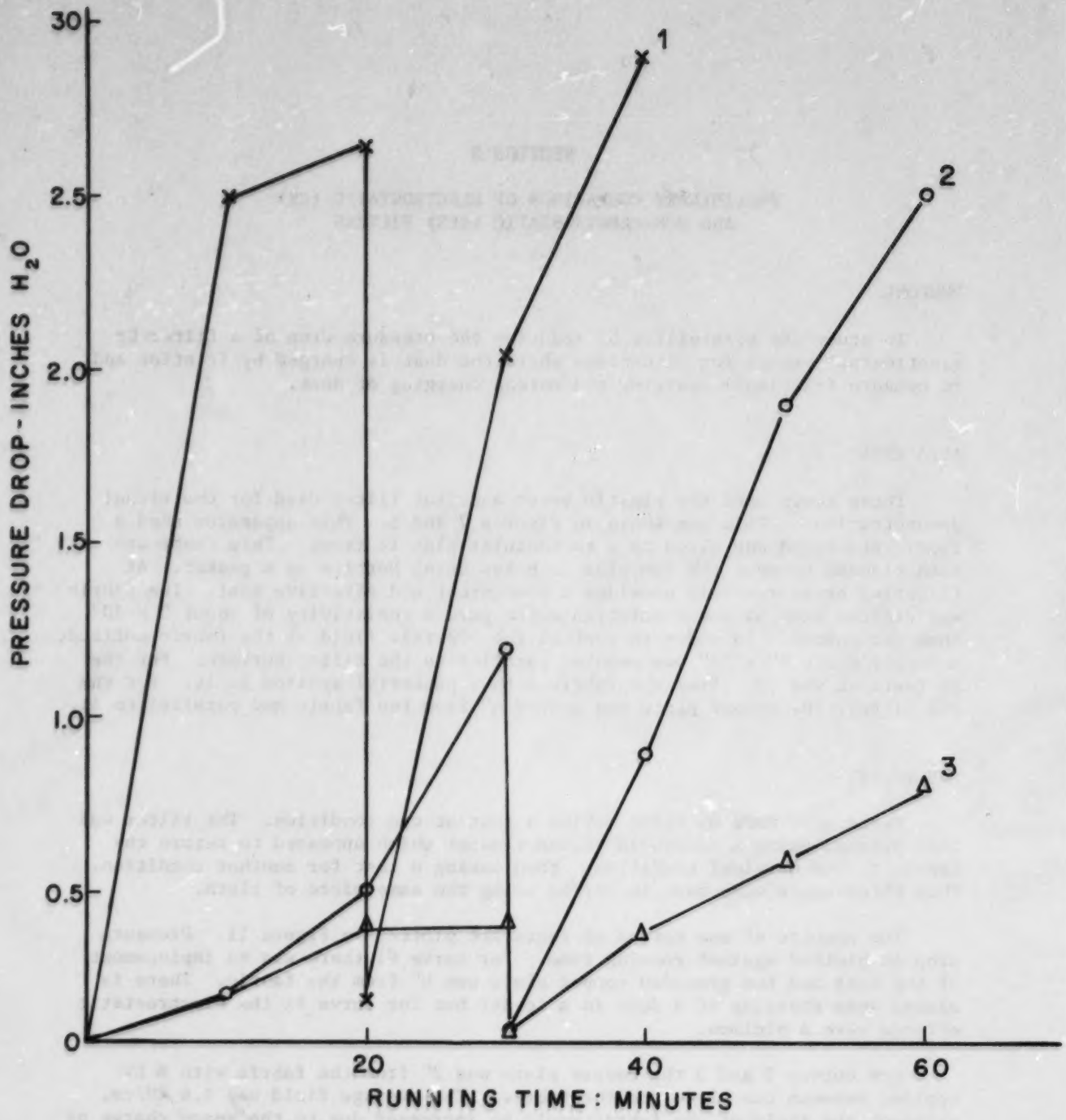


Figure 11 - Another Comparison of NES with ES Filtering

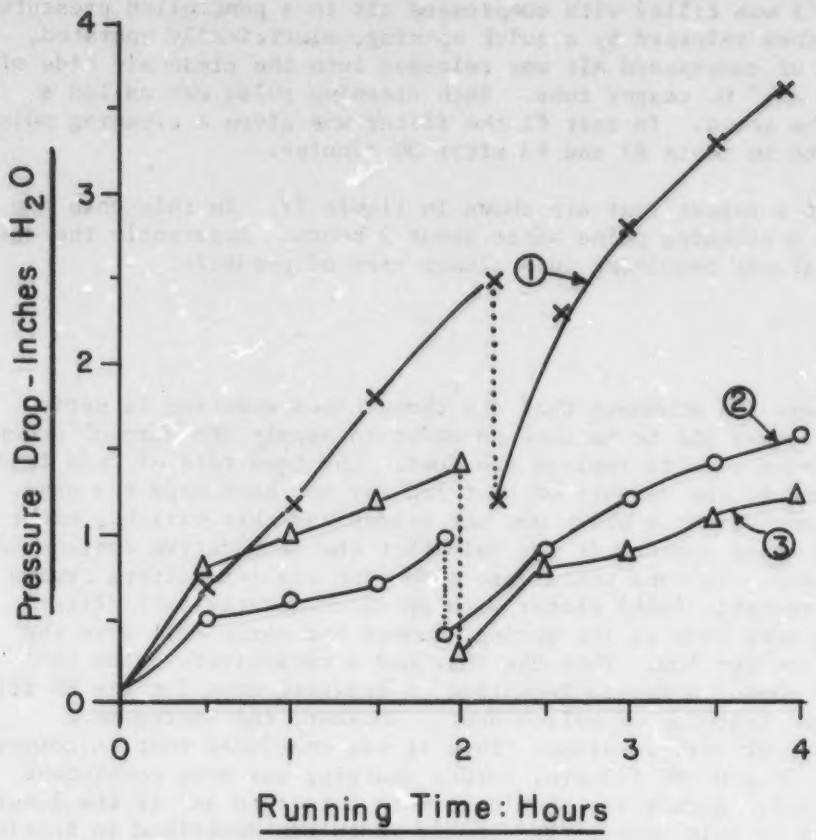
1. No Electric Field and Uncharged Dust (NES) Filtering
2. Dust charged by impingement against a tungsten carbide target. Average electric field of 1.6 KV/CM ES filtering.
3. Dust charged by corona. Applied field of 1.6 KV/CM average ES filtering.

The filters were cleaned by reverse air pulses. A small reservoir (approximately 75 in.^{2}) was filled with compressed air to a controlled pressure (5 to 15 lb.) and then released by a quick opening, electrically operated, valve. This pulse of compressed air was released into the clean air side of the filter through a ¼" D. copper tube. Each cleaning pulse was called a "pop" because of the sound. In test #1 the filter was given a cleaning pulse after 20 minutes and in tests #2 and #3 after 30 minutes.

The results of a repeat test are shown in Figure 12. In this case the filters were given a cleaning pulse after about 2 hours. Apparently the dust feed was a little slower resulting in a slower rise of pressure.

DISCUSSION

These tests have the weakness that the three tests were run in series. Our fluidized bed feeder had to be used on order to supply the aerosol under pressure to the nozzle used to impinge the dust. The feed rate of this feeder was not constant and so the density of dust fed may not have been the same. Also if there was any variable which was not recognized that variable might be different. For these reasons it was felt that the comparative tests should be run simultaneously. Various tests were made with smaller filters trying to compare a nonelectrostatic (NES) filter with an electrostatic (ES) filter. All of these tests were made in the spring, summer and early fall when the relative humidity was not low. Thus the dust had a resistivity below 10^{11} ohm-cm. All tests showed a marked reduction in pressure drop for the ES filter with impingement charging of silica dust. However, the impingement charging did not appear very constant. Thus it was concluded that to compare the performance of ES and NES filters, corona charging was more consistent and so should be used. Also tests should be much longer to see if the lower pressure drop could be maintained. The longer tests are described in Section 11 of this report.



Comparison of pressure drops for three electrostatic conditions.

① × **No charging of dust and no applied field.**

② ○ **Dust charged by impingement. Additional field of 8 kV across 5 cm.**

③ Δ **Dust charged by corona. Additional field of 8 kV across 5 cm.**

Filters cleaned by a reverse air pulse after approximately 2 hours.

Woven fabric with napped surface, permeability 30 CFM/ft^2 at 0.5 inches H_2O.

Silica dust, 5 grains per cubic foot.

Air to cloth ratio 3.7 fpm

Figure 12 - Comparison of NES with ES Filtering

SECTION 9

CONVEYING A CHARGED AEROSOL

THEORETICAL BACKGROUND

Metal Ducts

If in industry some process generates an aerosol in which substantially all particles carry the same sign of charge, special precautions would be required to convey this aerosol to a baghouse without loss of charge. The mutual repulsion of electric charges of like sign creates potentials which are described by Poisson's equation (Eq. 1 of Section 4). With a long cylindrical duct of 0.3 meters (0.98 ft.) diameter, a charge density of 10^{-4} coulombs/m^3 gives a field of 8.5×10^5 volts/m or 8500 volts/cm. Experience in electrostatic precipitators indicates that at this voltage gradient irregularities at the wall will cause corona which will act to neutralize the charge on the dust. A charge density of 10^{-4} coulombs/m^3 can readily occur with dust loadings of a few gr/ft^3 if all particles carry the same sign of charge. Thus ducts would have to be small. Furthermore this space charge field tends to precipitate dust on the duct walls and the small ducts required would present a large surface for dust collection.

Insulating Ducts

It might seem that charged dusts could be conveyed through insulating ducts without loss of charge. However, experience indicates that loss of charge is more probable with insulating ducts than with metal ducts. In our situation there will be a dust generator at one end and a filter at the other and both will normally be grounded. The insulating duct acts to concentrate the field at any grounded object and cause corona there which tends to discharge the dust.

The usual textbook treatment of electric fields discusses the case for alternating currents and voltages. In this A.C. case the voltage gradient through a dielectric varies inversely as the dielectric constant. Thus for the A.C. case the voltage gradient through a solid dielectric is lower than the gradient in air.

However with unipolar charged aerosols, the reverse is true. Charged particles will, initially, be driven by the electric field toward any containing wall. If the wall is an insulator it will acquire a charge until the field perpendicular to the wall is neutralized. Thus, in steady state, the field perpendicular to a perfect insulator will be zero. The field then becomes one-dimensional along the axis of the duct. This acts to produce high fields at the ends of an insulating duct, and especially high fields if any grounded conductor should puncture the insulating wall.

PURPOSE OF TESTS

The tests were intended to explore this worst case where some grounded point projects into an insulated duct, and to explore the kinds of effects that would have to be considered if a charged aerosol were to be conveyed over any distance.

APPARATUS

A DOP smoke was used because it is a very convenient and controllable source of fine particles. A diagramatic sketch of the apparatus is shown in Figure 13. The rates of flow of the incoming DOP and air are controlled independently and measured by orifices. These two streams combine and enter the charger. The corona charger consists of a 2" length of .012" D tungsten wire mounted along the axis of a 2" I.D. copper pipe. This charger connects to the test section which is an 8" length of 1½" I.D. PVC pipe such as used for plumbing. The test section leads to an absolute filter. The collected current is measured by an electrometer. The filter is followed by another orifice and fan. The details of the mounting for the absolute filter were shown in Figure 4. The filter is mounted between polystyrene insulating plates to insure that all of the collected charge flows to the electrometer. This assembly is mounted inside a grounded metal housing to shield the filter from stray fields and currents.

The first test section had four points projecting ¼" into the PVC pipe. Any one of these points could be connected by a clip lead to a Keithley electrometer and ground.

The second test section had one grounded point consisting of 0.12" D wire going radially to the axis of the pipe and then extending ½" axially and pointed up stream.

TEST RESULTS

Currents measured using the first test section have four probes or points are shown in Table 3. The current collected by the absolute filter was measured only when the current to probe A was being measured. Note that only one probe was grounded at any one time. Probe A was nearest the corona charger and so would be at a lower voltage point in aerosol stream. For 5% DOP the current to Probe A was only 1% of the current to the absolute filter. Currents to the other probes increased with distance from the charging section.

For 20% DOP the situation is very different. All probes give approximately the same current and the current to the filter is reversed in sign. This indicates that the corona from a grounded point can not only neutralize the original charge but can actually reverse the net charge in an aerosol. This reversal led to the second test section which was intended to accentuate this tendency to reverse the charge.

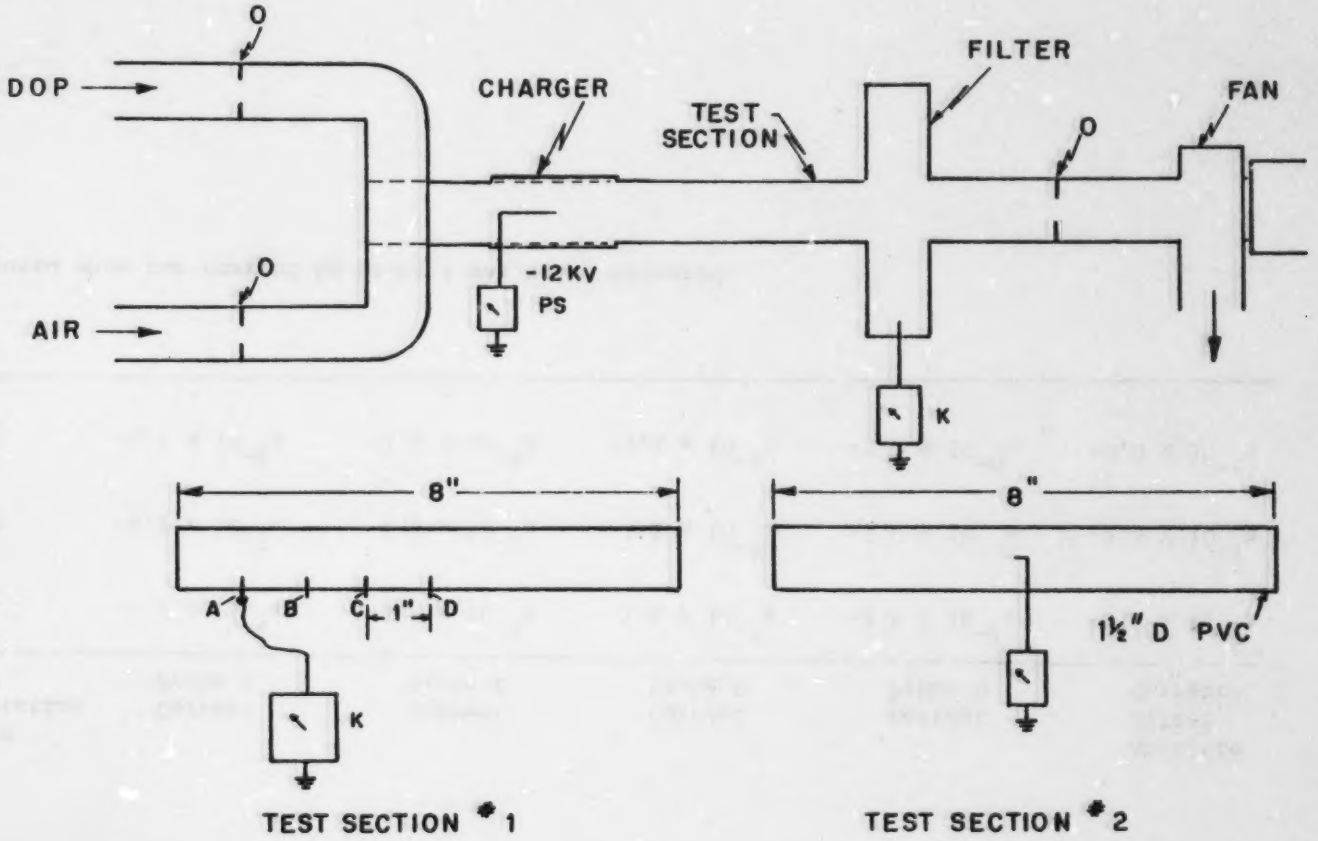


Figure 13 - Apparatus for Passing Charged Dust Through an Insulating Pipe and Measuring any Change in Charge

TABLE 3

CURRENTS MEASURED USING THE FIRST TEST SECTION

Relative Concentration of DOP	Current Probe A	Current Probe B	Current Probe C	Current Probe D	Absolute Filter Current*
5%	-2.5×10^{-9}a	-5.0×10^{-8}a	-1.1×10^{-7}a	-1.6×10^{-7}a	-2.5×10^{-7}a
10%	-4.2×10^{-7}a	-4.8×10^{-7}a	-5.5×10^{-7}a	-5.6×10^{-7}a	-1.6×10^{-7}a
20%	-1.1×10^{-6}a	-1.1×10^{-6}a	-1.1×10^{-6}a	-1.2×10^{-6}a	$+5.0 \times 10^{-3}$a

* Measured when the current to Probe A was being measured.

The currents obtained using the second test section are listed in Table 4. For 5% DOP the current to the probe is four times the current to the filter. The current to the filter first decreases as the percentage DOP increases, and at 12.5% DOP the sign of the current to the filter reverses. The current reversal increases as the percentage DOP increases. This again indicates the possibility that a grounded point can not only neutralize the charge on an aerosol but can also reverse the sign of the net charge.

The charge density of the aerosol leaving the corona charger is calculated assuming that there is no loss of charge except that to the probe and filter. Note that up to 12½% DOP the charge density is proportional to the percentage of DOP. Above 12½% DOP the charge density does not increase with particle density. These currents only increase due to the rate of gas flow.

This failure of the charge density to increase with the percentage of DOP illustrates the difficulty called "corona quenching" which occurs in the electrostatic precipitation of high particle densities. The charge density of the particles being charged reduces the corona current. Thus at any given gas velocity and ionizer voltage there is an upper limit to the charge that can be imparted to an aerosol. At this limit, as the number of particles per unit volume increases the average charge per particle must decrease.

DISCUSSION

These tests were only intended to indicate the difficulties if it should be necessary to convey a high charge density aerosol for any distance. The loss of charge due to corona can be controlled by using small metal ducts or by subdividing a larger duct. However the large area required provides a large surface where dust will be deposited by the electric field. This would be another troublesome problem.

TABLE 4

RESULTS OF TESTS WITH SECOND TEST SECTION

%DOP	Air (cfm)	DOP (cfm)	Current To Probe (amperes)	Current To Filter (amperes)	Calculated Charge Density Leaving Charger (coulombs/m^3)
5	10	0.5	-2.0×10^{-7}	-5.0×10^{-8}	0.504×10^{-4}
10	10	1.0	-5.4×10^{-7}	-1.0×10^{-8}	1.06×10^{-4}
12 1/2	10	1.25	-7.0×10^{-7}	$+5.0 \times 10^{-9}$	1.3×10^{-4}
15	10	1.5	-8.0×10^{-7}	$+4.0 \times 10^{-8}$	1.4×10^{-4}
17 1/2	10	1.75	-1.0×10^{-6}	$+1.5 \times 10^{-7}$	1.53×10^{-4}
20	10	2.0	-1.2×10^{-6}	$+1.7 \times 10^{-7}$	1.81×10^{-4}
25	10	2.5	-1.5×10^{-6}	$+2.5 \times 10^{-7}$	2.11×10^{-4}
30	10	3.0	-1.6×10^{-6}	$+3.0 \times 10^{-7}$	2.11×10^{-4}

SECTION 10

CHARGE CARRYING ABILITY (CCA) AS A MEANS FOR MEASURING PARTICULATES IN GASES

INTRODUCTION

To measure particulates by the CCA method the aerosol is passed through a corona discharge to impart an electrical charge to the particles. The aerosol is then passed through an absolute filter which collects the particles and their charges. An electrometer is used to measure the current due to the collected charge. This current then serves as a measure of the collected particles. This gives an instantaneous and continuous measure of particle density. For particles larger than 0.5 μm diameter, the charge is proportional to the square of the diameter. Below 0.3 μm diameter the charge per particle is proportional to the first power of the diameter. Thus the CCA method is especially sensitive to fine particles.

There is a very serious limitation to the use of the CCA method. The aerosol must be charged by passing through a corona discharge. If the resistivity of the dust is greater than about 2×10^{10} ohm-cm back corona may occur and prevent proper charging of the particles. In the tests reporte in Section 12 three aerosols were used, kerosene smoke, tobacco smoke, and welding smoke. The kerosene smoke and the tobacco smoke both have a sufficiently low resistivity. Welding smoke could cause trouble at humidities of 15% or lower, but we made these tests at higher humidities where resistivity was not a problem.

The other method which we considered was light scattering. This is widely used for measuring 0.3 μm diameter particles. However for particles small as compared to the wave length of light the light scattered varies as the sixth power of the diameter. Thus CCA is much more sensitive than light scattering for measuring particles smaller than 0.2 μm diameter.

APPARATUS AND TEST PROCEDURE

The general arrangement is shown in Figure 14. The air enters through 1½" PVC pipe which serves as insulation for the high voltage lead. The corona wire is .012" D tungsten and extends about 1½" inside the copper tube. The 2" I.D. copper tube serves as the grounded electrode for the corona and for collecting air ions. Under some conditions there will be a significant number of air ions carried downstream from the corona. If not removed they would cause a false reading. These air ions have a high mobility so that they can be removed by a weak field which removes only a negligible fraction of the dust particles. This is done by applying 75 volts to electrode 8 which is 3/8" D by 6" long.

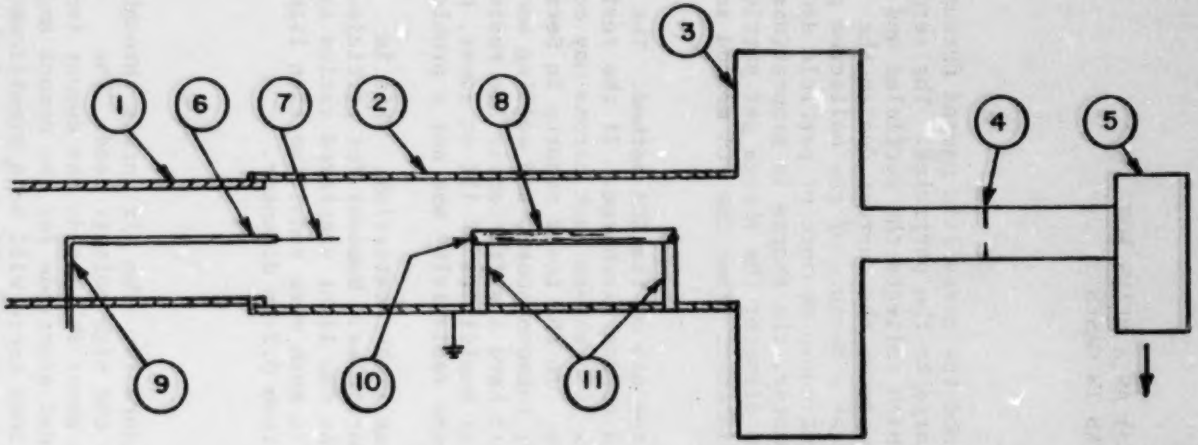


Figure 14 - Diagramatic Sketch of Apparatus for Measuring Charge Carrying Ability (CCA)

The construction of the charge collecting filter was shown in Figure 4. It consists of a high efficiency (HEPA or Absolute) filter mounted between polystyrene insulating plates. A current measuring lead is fastened to the filter frame. Under most conditions the filter media would have adequate conductivity to carry the minute currents involved. However to facilitate current conduction, conducting paint is used to paint stripes from the wire to the ridges or folds of the filter. A Keithley Electrometer is used to measure the current collected from the particles.

The corona wire is operated at a voltage to give about 15 microamperes corona current. The electrode for removing air ions is operated at 75 volts.

On an average fall day at Carnegie-Mellon University the CCA of the air is of the order of 5×10^{-8} coulombs/m^3. The instrument can measure up to 10^{-4} coulombs/m^3 without diluting the incoming air. For our tests the air flow was 3 cfm. The manufacturer's rating of the filter was 30 cfm at 1.0" water pressure drop. At this low flow the filter has a very high dust holding capacity and so a long life. We have used this method to measure down to 5×10^{-10} coulombs/m^3, i.e., 1% of the normal particulates in Pittsburgh air. It appears possible to go appreciably below this.

The ionizer should not be operated below 3 cfm or there will be excessive collection in the ionizer. For continuous monitoring of high density aerosols, the aerosol should be diluted so that only a low density aerosol is passed through the filter. This is desirable in order to prolong the life of the filter.

DISCUSSION

This method for measuring fine particulates is very useful in a laboratory where the operator knows how to recognize and avoid troubles due to back corona and will clean the corona chamber when needed. The method can be used to measure a wide range of dust densities and is much more sensitive than light scattering for particles below 0.3 μm diameter. More work is needed to develop a method that is suitable for general use.

SECTION 11

COMPARATIVE MEASUREMENTS OF PRESSURE DROP IN FABRIC FILTERS

PURPOSE

This series of tests was devised to compare the pressure drop of a conventional filter with one in which the dust is electrically charged and in which there is an electric field to drive this charged dust toward the fabric surface.

METHOD

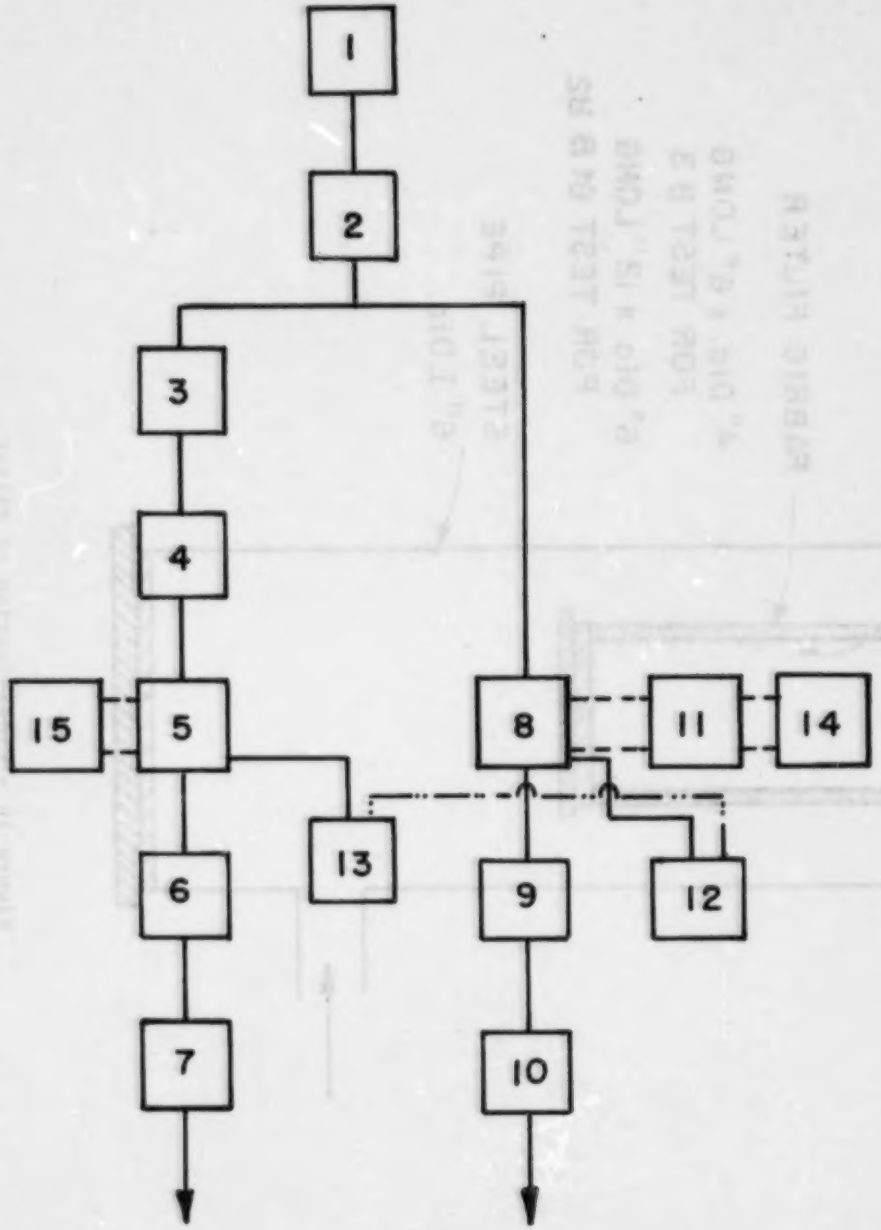
A dust stream is divided into two equal parts. One stream goes to a conventional filter with no charging of the dust nor applied voltage; this is called the non-electrostatic (NES) filter. The other dust stream is passed through a corona charger and to a filter where an applied voltage produces an electric field perpendicular to the filter surface; this is called the electrostatic (ES) filter. The pressure drops of the two filters are then compared over the test period.

In our experience corona charging is more consistent than impingement charging. Accordingly corona charging was used in these comparative tests.

APPARATUS

A block diagram of the apparatus is shown in Figure 15. Dust from the feeder (1) goes to a venturi (2) where a compressed air jet disperses the dust. The dust stream then divides into two equal parts. The left hand stream goes through a corona charger (3). Next there is a heater (4) which by heating the air can raise the resistivity of the dust. This heating section was used only in the second test (B-2). It was removed for the other tests. The dust then goes to a filter (5) the details of which are shown in Figure 16. From the filter the cleaned air goes through a measuring orifice (6) and to a fan (7) whose speed can be adjusted to maintain the desired air flow. The right hand dust stream goes directly to the NES filter (8), an orifice (9), and fan (10).

Recording pressure meters, (14) and (15), record the pressure drop across each filter. Both filters are cleaned by identical and simultaneous bursts of compressed air (called "Pops" because of the accompanying sound). A pressure switch (11) triggers the air valves (12) and (13) which release air from two identical compressed air chambers.



1	DUST FEEDER
2	VENTURI
3	IONIZER
4	HEATER
5	ELECTROSTATIC FILTER
6,9	MEASURING ORIFICES
7,10	FANS
8	NON-ELECTROSTATIC FILTER
11	PRESSURE SWITCH
12,13	REVERSE AIR VALVES
14,15	PRESSURE RECORDERS

Figure 15 - Block Diagram of Apparatus for Comparison of ES and NES Filters

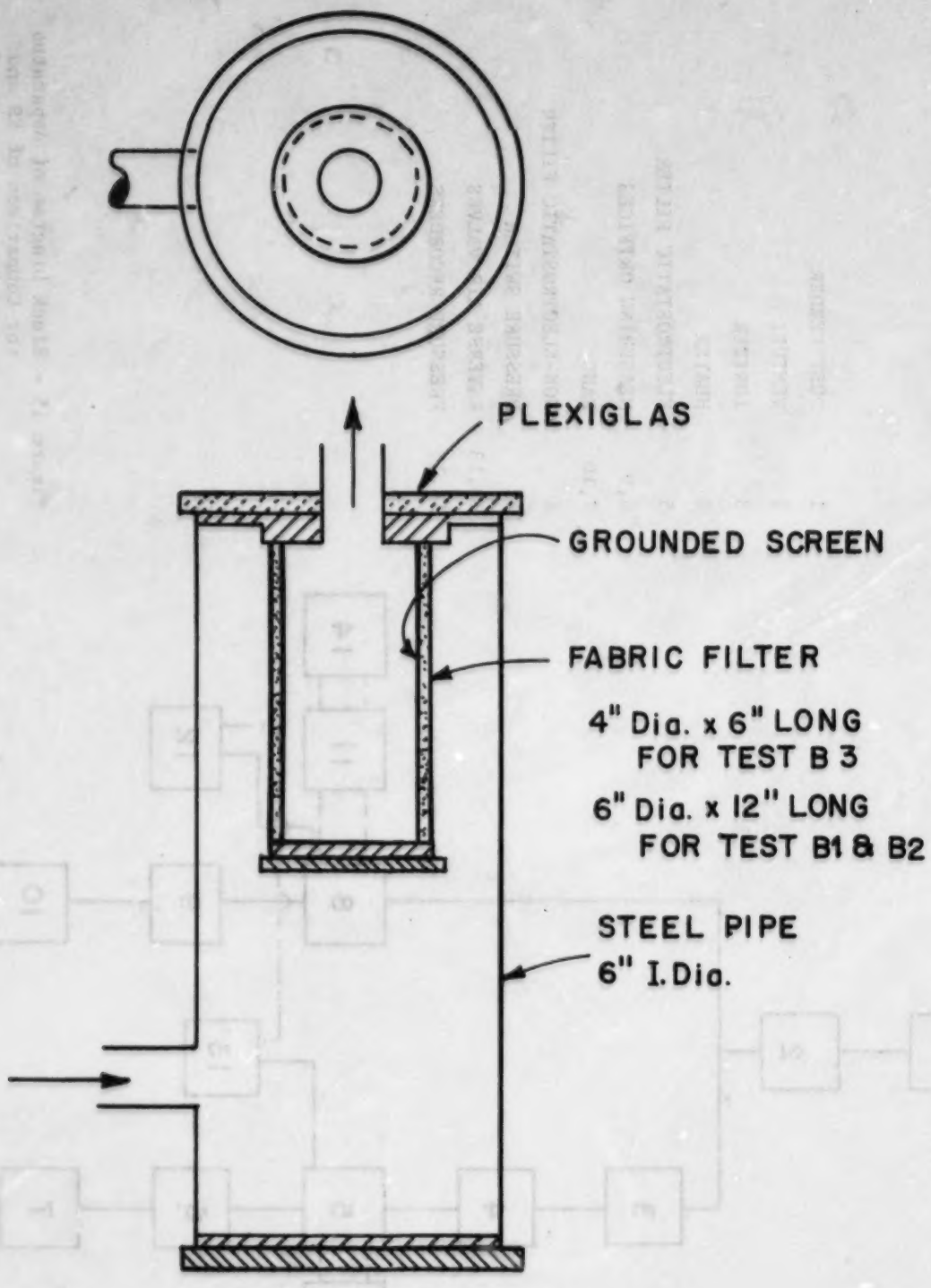


Figure 16 - Cross-Section of Filter

THE TEST RESULTS

Test B-1

The results of the first test are shown in Figure 17. Pressure drop vs. time is plotted for each filter. In this case the pressure drop for the NES filter is always higher than that for the ES filter. This test was run at room humidity (40 to 50%) at which the resistivity was below 2×10^{10} ohm-cm. The test dust was ground silica rock. The air-to-cloth ratio was 6.

Test B-2

This test was made to explore two questions; a) the possibility of operating at a higher air-to-cloth ration, and b) the effect of higher resistivity of the dust. Pressure drop vs. time is plotted in Figure 18. For the first 26 hours both filters were operated at room humidity (45 to 50%) which resulted in a dust resistivity below 2×10^{10} ohm-cm. For the first 45 hours both filters were operated at an air-to-cloth ratio of 12.

Numerals on the chart refer to the following changes in operation:

1. At this point (hour 4) there were several cleaning cycles (Pops).
2. At hour 26, heater 4 was activated to increase the temperature of the air going to the ES filter to 113°F. This corresponds to a dust resistivity of about 7×10^{11} ohm-cm.
3. At hour 31-½ temperature was further increased to raise the ES filter air temperature to 150° - RH 6% - or a dust resistivity of 10^{13} ohm-cm.
4. At hour 41-½ the NES filter was given many quickly repeated cleaning cycles (Pops) thinking that the filter might clean to a lower pressure drop. But the record shows that after 2 cycles a "pop" only reduced the pressure drop from 10" to 8".
5. At hour 45 the air-to-cloth ratio of the NES filter was reduced to 6. The ES filter remained at 12. At this condition the pressure drop overlap is shown by the double cross hatching. Remember that both filters are "popped" simultaneously whenever the NES filter reaches 10" pressure drop. The lower line of the double cross hatched area is the pressure drop of the NES filter just after a "pop". The charge density of the aerosol going to the ES filter averaged about 2×10^{-5} coulombs/m^3. However the feed rate was somewhat variable resulting in fluctuations in the charge density.

The parameters for tests B-1 and B-2 are given in Tables 5 and 6. The dust loadings are determined by weighing the dust collected for the entire period. A small stream of filtered air is passed through a Gelman filter for the entire period and this gives the dust loading leaving the filter. This in combination with the entering dust loading gives the average efficiency.

In tests B-1 and B-2 the attempt is to have the dust loading entering the NES filter equal to that entering the corona charger for the ES filter. The corona charger removes some dust. Thus the dust entering the ES filter

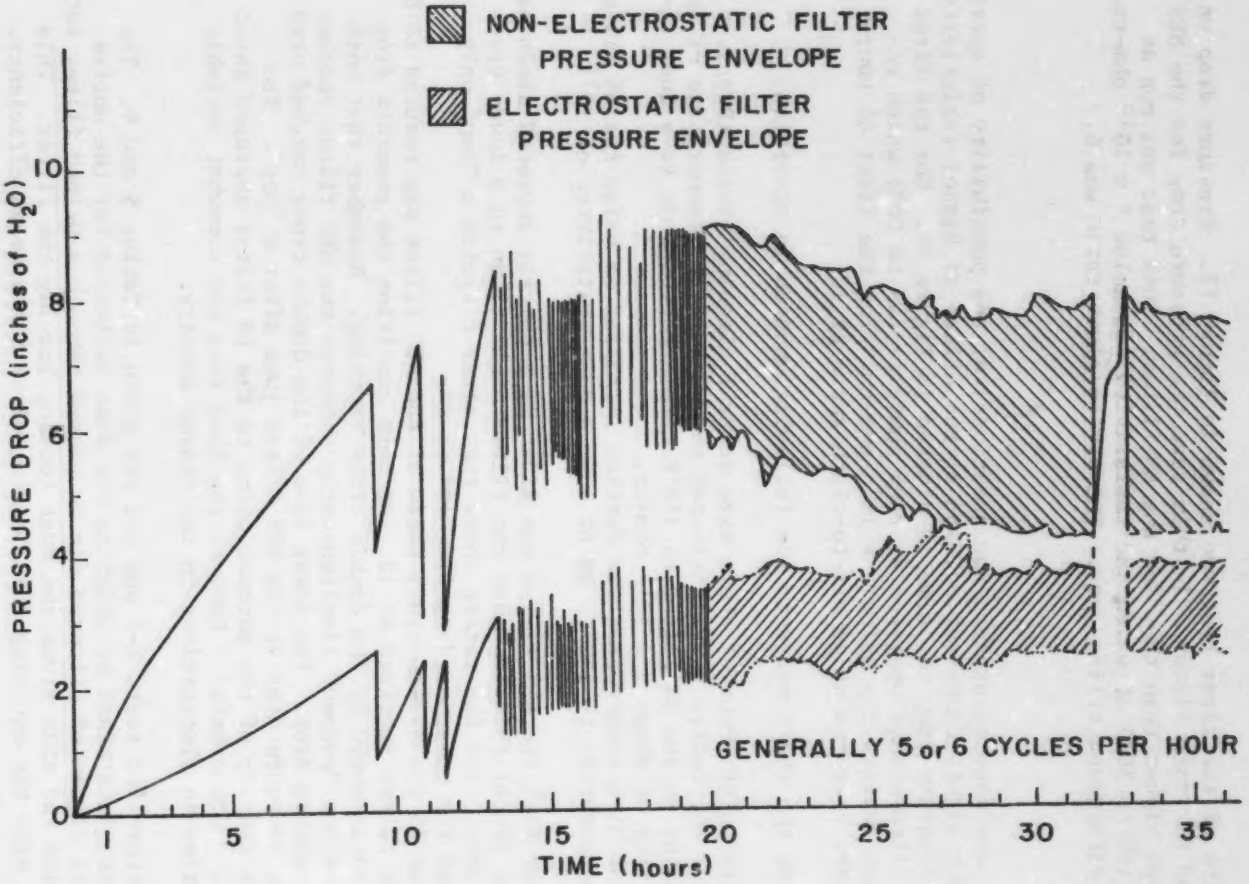


Figure 17 - Pressure Drop vs. Time - Test B-1

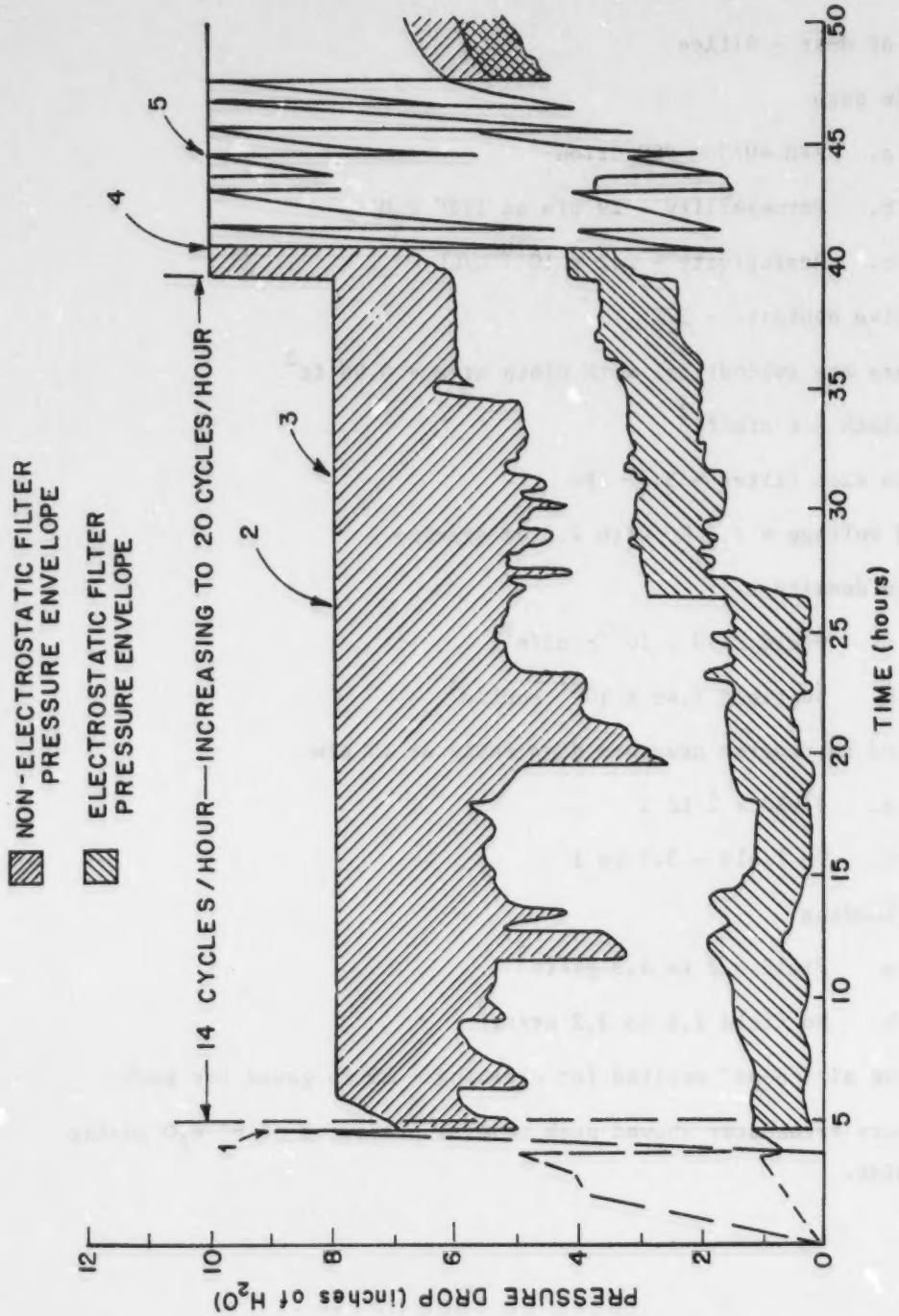


Figure 18 - Pressure Drop vs. Time - Test B-2

TABLE 5

CONDITIONS FOR TEST B-1

Type of dust - Silica

Fabric data

a. AFC 40/300 #99 Orlon

b. Permeability - 29 cfm at 1/2" H_2O

c. Resistivity - 2.2×10^{10} Ω/□

Relative humidity - 37%

Filters are cylindrical with cloth area = 0.96 ft^2

Air/cloth - 6 cfm/ft^2

Air to each filter = 5.75 cfm

Field voltage = 7.5 Kv with 2.5 cm spacing

Charge density

a. Field 2.98×10^{-5} $coul/m^3$

b. No field 7.45×10^{-7} $coul/m^3$

Forward to reverse pressure drop ratio at 10 cfm

a. Field - 2 to 1

b. No field - 3.7 to 1

Dust Loading

a. Field 4.2 to 4.3 gr/ft^3

b. No field 2.8 to 3.2 gr/ft^3

Reverse air "pops" applied for cleaning - 20 lb gauge for each

Pressure transducer showed peak reverse pressures of 6" H_2O during cleaning.

TABLE 6

CONDITIONS FOR TEST B-2

Type of dust - Silica

Fabric data

a. AFC 40/300 #99 Orlon

b. Permeability - 22.5 cfm at 1/2" H_2O

c. Resistivity - 2×10^{10} Ω/□

Relative humidity at ionizer 47%

Filters are cylindrical with cloth area = 0.96 ft^2

Air/cloth = 6 cfm/ft^2

Air to each filter = 5.75 cfm

Field voltage = 7.5 Kv with 2.5 cm spacing

Charge density

a. Field $2.6 \times 10^{-5} coul/m^3$

b. No field $3 \times 10^{-6} coul/m^3$

Dust densities

a. Field 1.6 to 2.10 gr/ft^3

b. No field 2.8 to 3.2 gr/ft^3

Reverse air "pops" applied for cleaning - 50 lb gauge for each

is less than that entering the NES filter.

Test B-3

In this test the position of the corona charger was changed. The charger for test B-3 was immediately after the feeder so that the air entering both filters was charged. This was done so that the dust loading for both filters would be the same. Thus there was a slight field at the NES filter due to the space charge of the dust. The calculated field at the NES filter was 100 volts/cm. This compares with an applied field of 3000 V/cm in the ES filter. Thus the NES had a slight electrostatic effect but apparently not enough to seriously affect the pressure drop.

The primary purpose of Test B-3 was to compare the first operating cycle of ES and NES filters, starting with clean cloth.

In this test each filter was operated without cleaning until it had reached 10" pressure drop. In this case the filters were shorter, 6" long instead of 12" long, but otherwise the same as in test B-1. This test differs from test B-2 in that the filters in test B-2 are 12" long also in test B-2 there was a heater between the corona charger and the ES filter. There was no heater in tests B-1 and B-3. The test parameters are tabulated in Table 7 and pressure drops plotted as a function of time in Figure 19.

Another modification in Test B-3 was that 3" x 3" windows were cut in the enclosing 6" D steel cylinders. These windows were provided with removable covers. Thus by removing the covers the dust deposit could be observed and photographed at various times during the test.

In this test it appeared that in the ES filter the dust deposited electrostatically on the lower part of the cylinder leaving some cloth relatively clean. This appears to account for the low pressure drop of the ES filter for the first 14 hours of operation. We cannot explain why this effect was so much more pronounced in this test than in the previous two tests.

A photograph, Figure 20, taken through the window midway through the test shows how the top left side of the filter is relatively clean. At the lower right hand corner some dust appears to have fallen off. A close-up photograph of the lower part of the dust deposit is shown in Figure 21. Note that the silica dust forms fiber-like deposits. Early in the test the two filters were removed so that a photograph could be taken to compare the two types of dust deposit. This photograph is shown in Figure 22. The ES filter is on the left. The upper half of the filter is almost clean. The NES filter is on the right. Here the dust deposit appears relatively uniform and comparatively compact.

A SECOND RESISTIVITY LIMIT

When electrically charged dust is collected on a filter, the charge on the deposited dust must be conducted through the filter cake to the fabric and to ground. Thus far it has been assumed that the dust is sufficiently

TABLE 7

CONDITIONS FOR TEST B-3

Silica dust fed using geartooth dust feeder and Venturi nozzle with 10 lb pressure applied.

Cloth area = .5 ft^2

Air/cloth = 6 cfm/ft^2

Cylindrical filters used with removable window

Field spacing = 2.5 cm

Applied field voltage = 8.5 Kv

Fabric is AFC #115 50% wool 50% acrylic. Fabric resistivity is 5.9×10^{10} $\Omega/\square$.

Fabric permeability = 130 cfm @ .5" H_2O.

Test data

	Field	No field
Dust collected by filter	971.2 g	208.7 g
Dust loading	4.50 gr/ft^3	4.64 gr/ft^3
Deposit depth	.815 cm*	.235 cm
Deposit weight	65.4 g	33.6 g
Deposit density	.173 g/cm^3	.307 g/cm^3
Time required for filter to reach 10" H_2O	18.0 hr	3.75 hr
Weight efficiency	99.69%	

*Estimated average depth

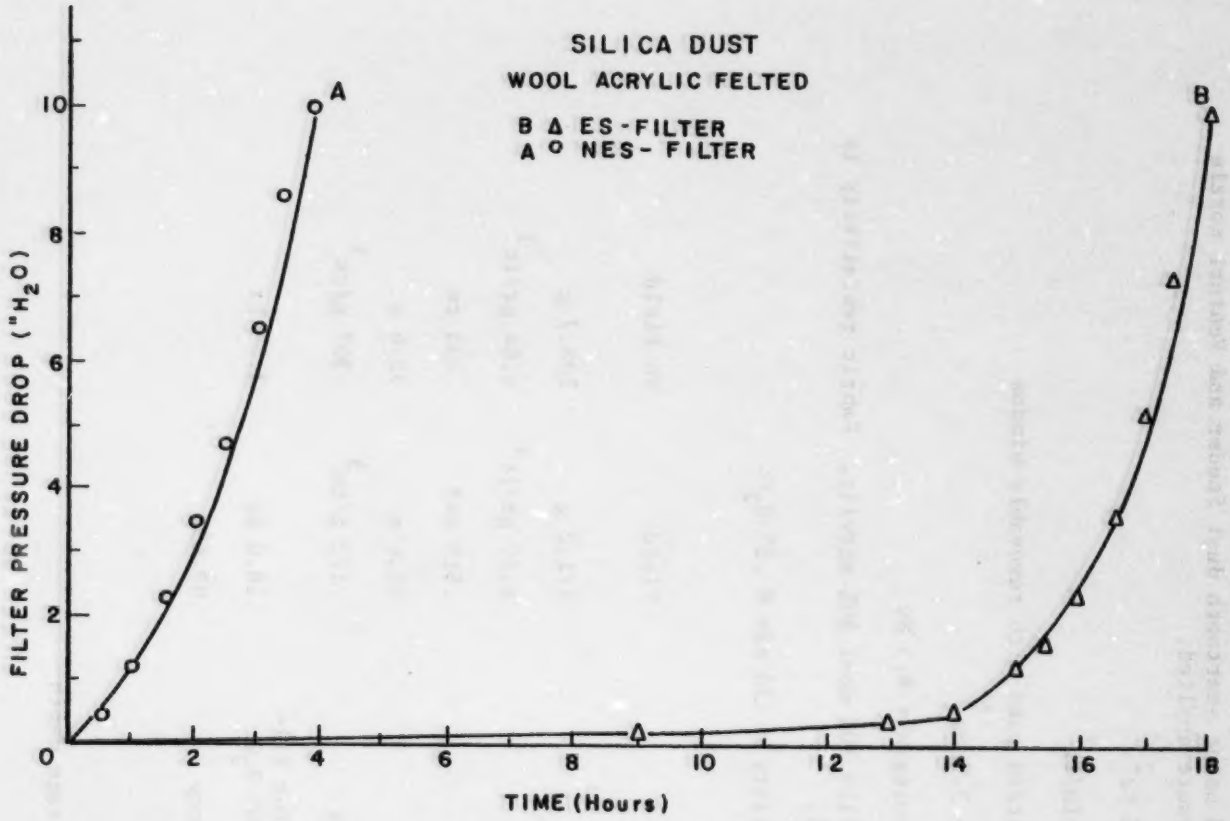


Figure 19 - Pressure Drop vs. Time - Test B-3

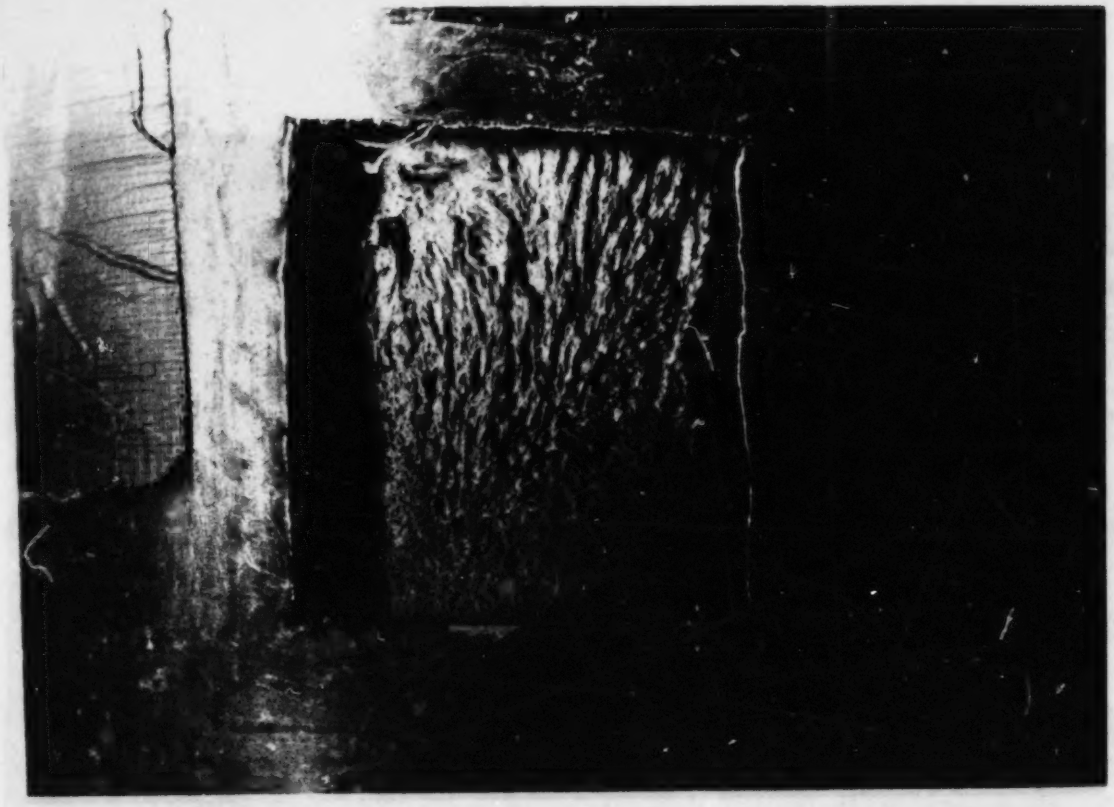


Figure 20 - Filter As Seen Through the Window

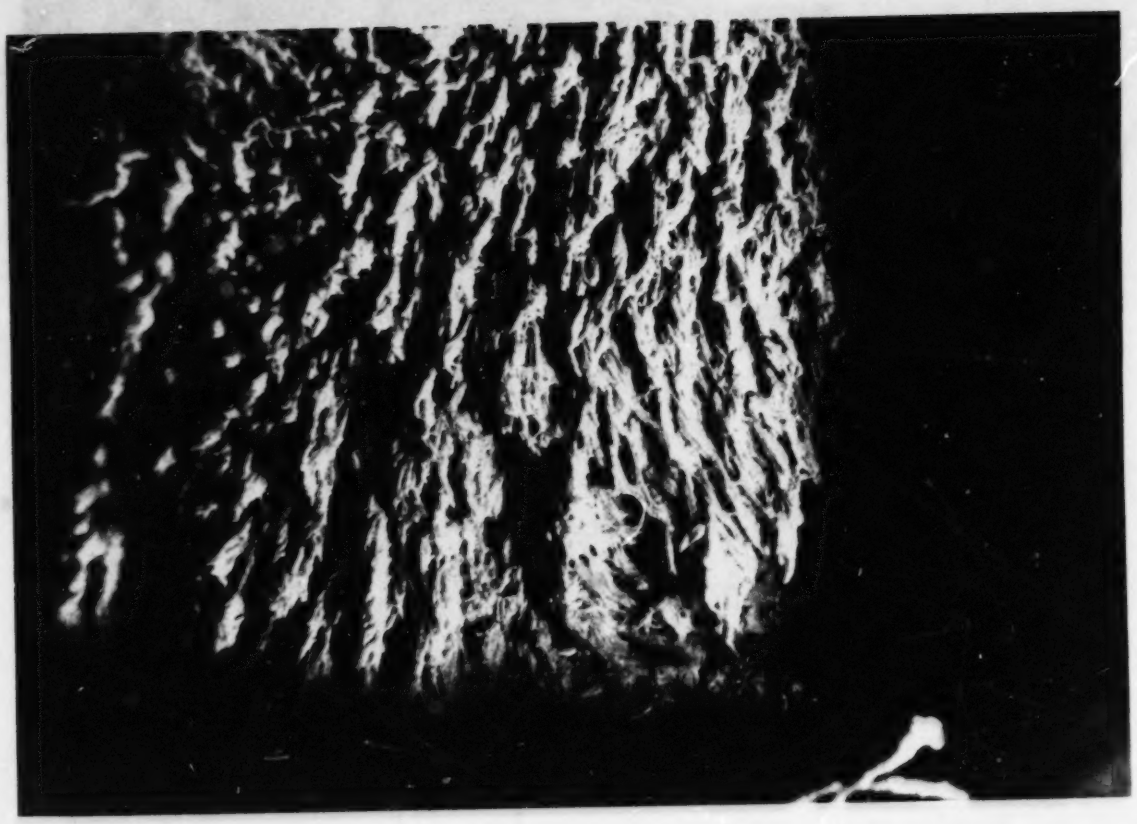


Figure 21 - Close-Up View of Dust

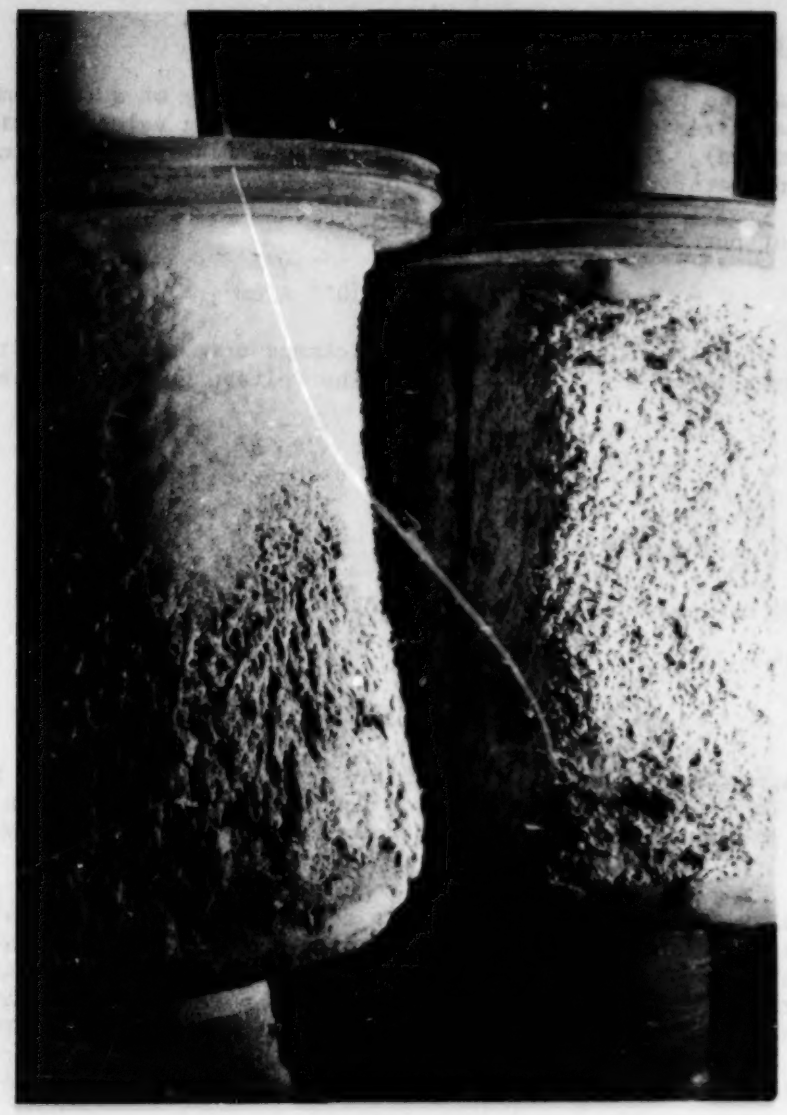


Figure 22 - Photograph Showing Both Filters Early in the Test

conducting so that the voltage drop or gradient in the dust is small. However there will be some resistivity at which this will not be true.

Example or Analysis

Assume that the charged aerosol has a charge density of q (coulombs/m^3) and the dust has a resistivity ρ (ohm-cm). The filtering velocity (air/cloth ratio) is V (cm/sec). Since it is customary to specify resistivity in ohms-cm we will use centimeter rather than meter in the calculation.

The current per cm^2 is:

$$i = q/10^6 \times V = qV \cdot 10^{-6} \text{ A/cm}^2 \qquad (7)$$

The resistance of a cm^2 of filter cake of thickness t is ρt. The voltage drop in the dust layer is $\rho t \cdot qV \cdot 10^{-6}$ volts. The voltage gradient in the dust layer is

$$E = \frac{\rho \cdot t \cdot q \cdot V \cdot 10^{-6}}{t} = \rho \cdot q \cdot V \cdot 10^{-6} \text{ volts/cm} \qquad (8)$$

Assume $q = 10^{-5}$ coulombs/m^3.

Assume V = 3.04 cm/sec (air cloth = 6 ft/min).

If $\rho = 10^{14}$ Ω cm:

$$E = 10^{14} \cdot 10^{-5} \cdot 3.04 \cdot 10^{-6} = 3.04 \times 10^3 \text{ volts/cm.}$$

This is approximately equal to the field that can be applied at the filter surface. Thus the dust surface can no longer be considered as an equipotential and in theory there would be no tendency to produce a porous dust layer.

The resistivity of dust depends on the contact between individual particles. As measured for electrostatic precipitation the dust is reasonably compact. However when dust is deposited on a filter in the porous form, microscopic examination indicates that the particles often have a chain-like formation with apparently poor contact between adjacent particles. Thus the resistance of a filter cake may be consideralby higher than would be indicated by the conventional resistivity as determined for ESPs.

Note that the electric gradient in the dust layer (Eq. 8) is proportional to the product of resistivity by charge density. The value of 10^{-5} coulombs/m^3 is fairly representative but it could be as high as 10^{-4}. On the other hand with low dust loadings the charge density could be quite low. Thus the critical resistivity is dependent on the charge density and the air/cloth ratio.

In test B-2 the charge density averaged about 2×10^{-5} coulombs/m^3. At the end of the test the charged aerosol was heated so as to give a dust resistivity of 10^{13} ohm-cm. The test is far from conclusive but it indicated that at 10^{13} pressure drop was not as low as for a lower resistivity dust.

This is in reasonable agreement with the above calculation. In fact it is a better agreement than we expected. We had expected that the porous nature of the dust would cause a very large increase in resistivity. Thus it had been considered probable that at a resistivity of 10^{13} the ES filter would show no advantage.

Charging some dust positively and some dust negatively, mixing these two and applying a potential between parallel filter surfaces is described in U.S. Patent #3,966,435. In this case the positive dust would be drawn to the negative dust to the positive filter. In case the dust is naturally charged with positive and negative polarities only the voltage between filters is needed.

A company was interested in this possibility and supported tests to see if it could be applied to one of their problems. It was found that in that particular case, there was the necessary mixture of + and - particles. At room temperature and a high humidity (> 50%) the dust had a low resistivity and a marked reduction in pressure drop was obtained. However in their application the dust was at a temperature such that the resistivity was greater than 10^{13} Ω cm. When this resistivity was duplicated in the laboratory the pressure drop of the ES filter was essentially equal to the NES filter. No further work was done.

DISCUSSION AND CONCLUSIONS

The primary purpose of these tests was to compare an ES filter with a NES filter. Since static is dependent on the atmosphere and since the dust may be variable, the filters being compared were operated simultaneously, using filters cut from the same piece of cloth, and operated from the same dust stream. In all cases the ES filter showed a distinctly lower pressure drop than the NES filter.

There are important differences between the different tests. In test B-3 the ES filter operated at a very low pressure drop for the first 14 hours. The other tests did not exhibit this low initial rate of rise of pressure. We can only speculate as to the cause. Apparently the low rate of rise of pressure was due to the fact that the upper part of the filter remained almost clean for this 14 hour period. Observations made through the removable 3" x 3" section indicated that the dust was being electrostatically precipitated on the lower part of the filter. However we do not know why this did not happen in the other tests.

These tests indicate that, under the proper conditions, a significant reduction in pressure drop can be obtained, if the particles are charged, and if there is a field driving the particles toward the filter. However we do not know of any industrial situation in which the particulates have the necessary charge as the dust originates. Also most dusts have too high resistivity for satisfactory charging by corona. So there is no obvious application in industry. If work on precipitation should develop a means for charging high resistivity dust that would open up new possibilities both in precipitation and filtration.

While the possibility of reducing pressure drop in a filter appears to be established, many questions would have to be investigated before a reliable process could be developed. We are not investigating these questions further because the work does not appear to be economically justified until there is some probability of industrial application.

SECTION 12

ELECTROSTATIC AUGMENTATION OF EFFICIENCY OF FABRIC FILTERS

INTRODUCTION

In Section 11 it was shown that electrically charged dust in combination with an electric field driving particles toward the filter can materially reduce the pressure drop. Since this deposit is more porous it raises the question that the filter may be less efficient.

PURPOSE

To measure the effect of particle charge and electric field on the efficiency of collection of fine particles.

THE TESTS

In preliminary tests, tobacco smoke, atmospheric air, kerosene smoke, and smoke generated by an electric arc were all tried as test aerosols. All gave similar increases in efficiency but the electric arc smoke seemed to be the most reproducible and so was used for the tests. Some preliminary tests were made using a filter having a previously deposited filtercake of other dusts. However a clean fabric filter was subject to less variation and was more definable and so each test started with a clean fabric. Charge carrying ability is especially sensitive to fine particles and the test can be made quickly and so was used in these tests.

A dilute smoke was used and the tests were made rapidly so that there would be a minimum formation of filter cake and consequent change in efficiency during the test.

The filter used was 4" diameter by 6" long inside a 6" diameter steel tube as shown in Figure 16. Each test started with a new piece of fabric.

First efficiency was measured as a function of face velocity with no applied field and no corona charging. This curve is labeled "A". Next the test was repeated with an applied field. This curve is labeled "B". Finally the test was repeated with the aerosol charged by corona and with an applied field driving the charged particles toward the filter (curve "C").

Comparative efficiencies are shown for different fabrics in Figures 23, 24, 25, 26 and 27. With charged particles and an electric field the efficiency is 99% or better at 2 ft/min through the fabric. For the #92 Darvan the

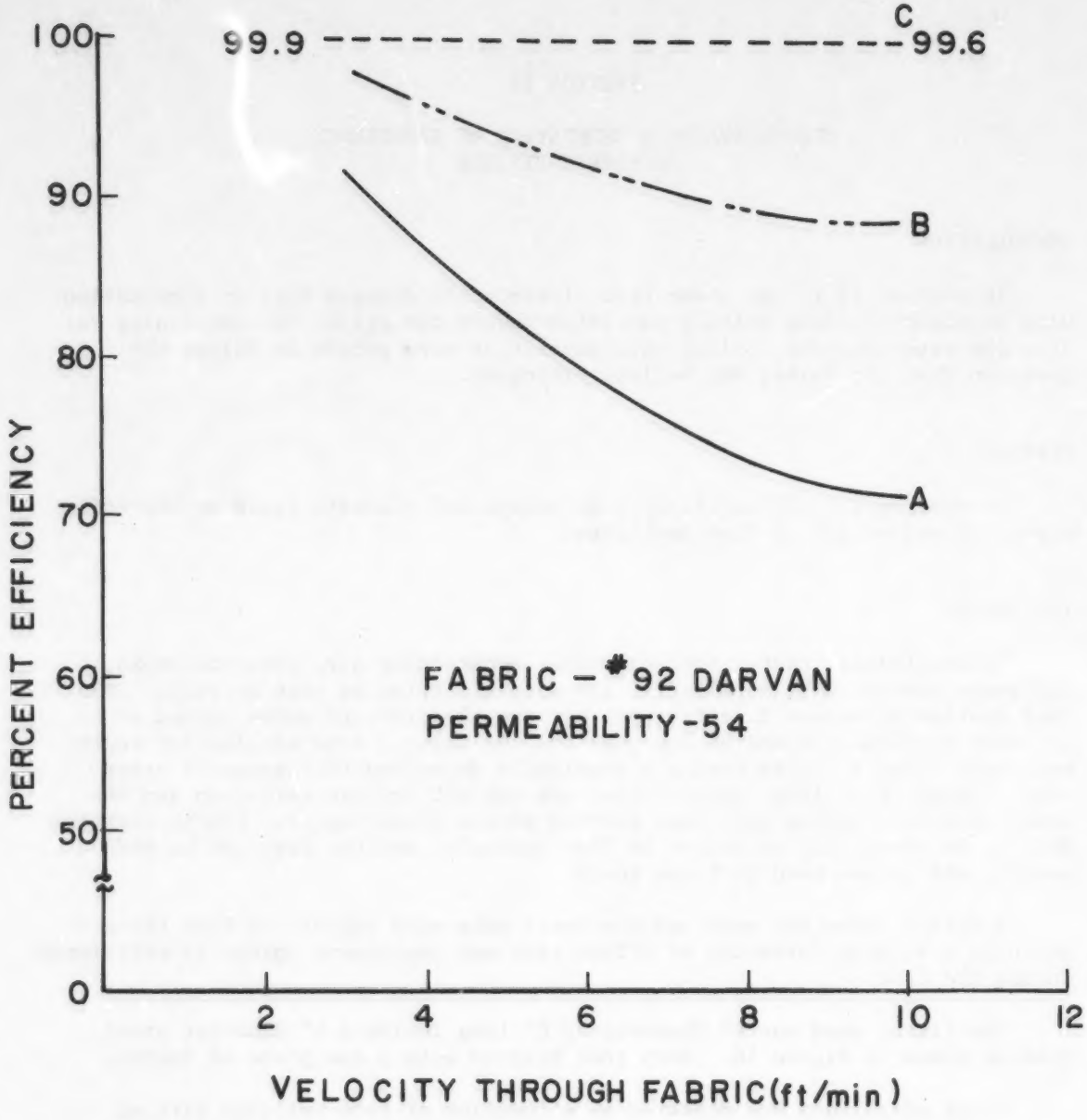


Figure 23 - Electrostatic Augmentation of Efficiency of Clean Darvan Fabric

A - No field no charging
B - Electric field, no charging
C - Electric field and charged dust

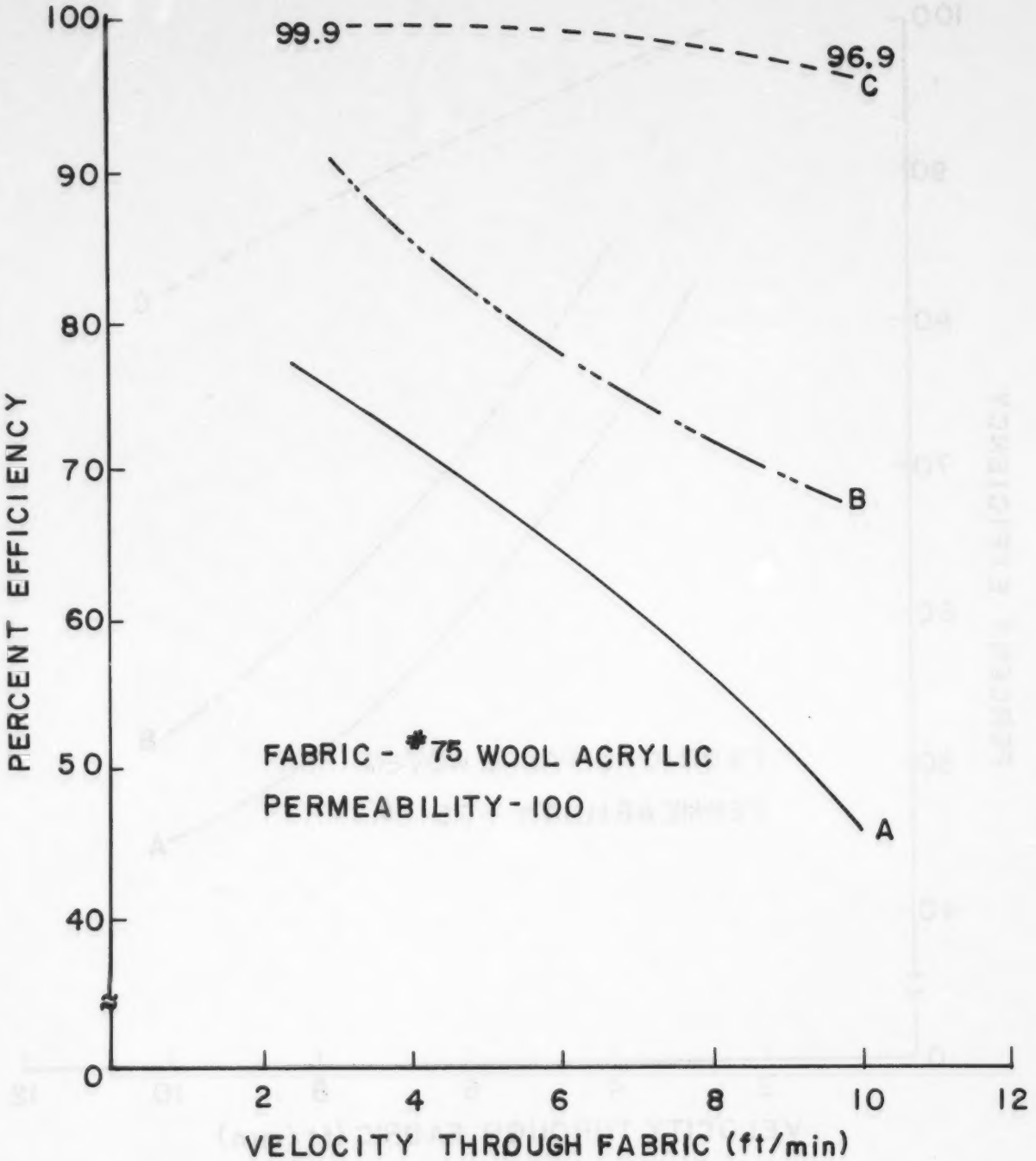


Figure 24 - Electrostatic Augmentation of Efficiency of Clean Wool-Acrylic Fabrics

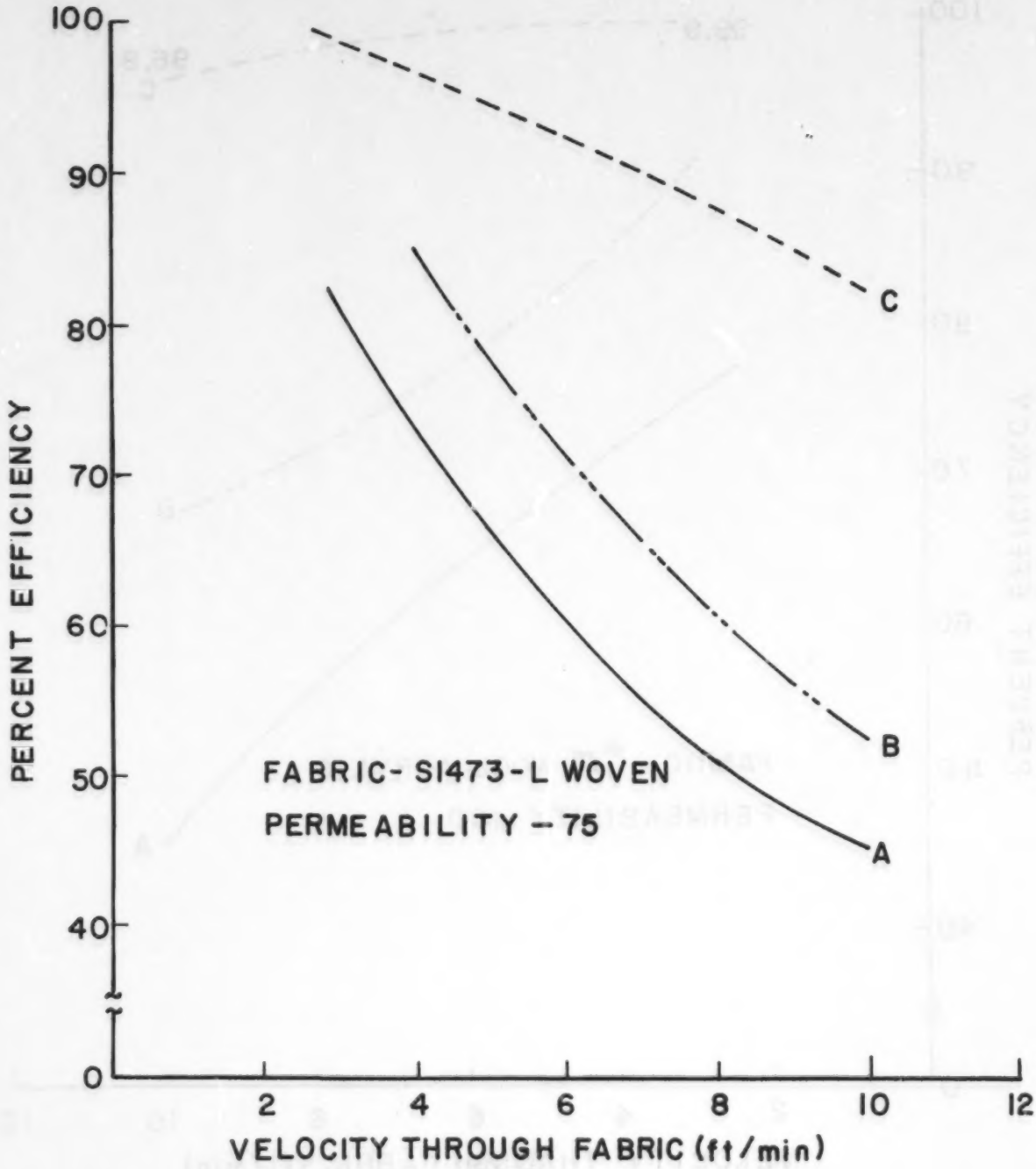


Figure 25 - Electrostatic Augmentation of Efficiency of a Clean Woven Fabric

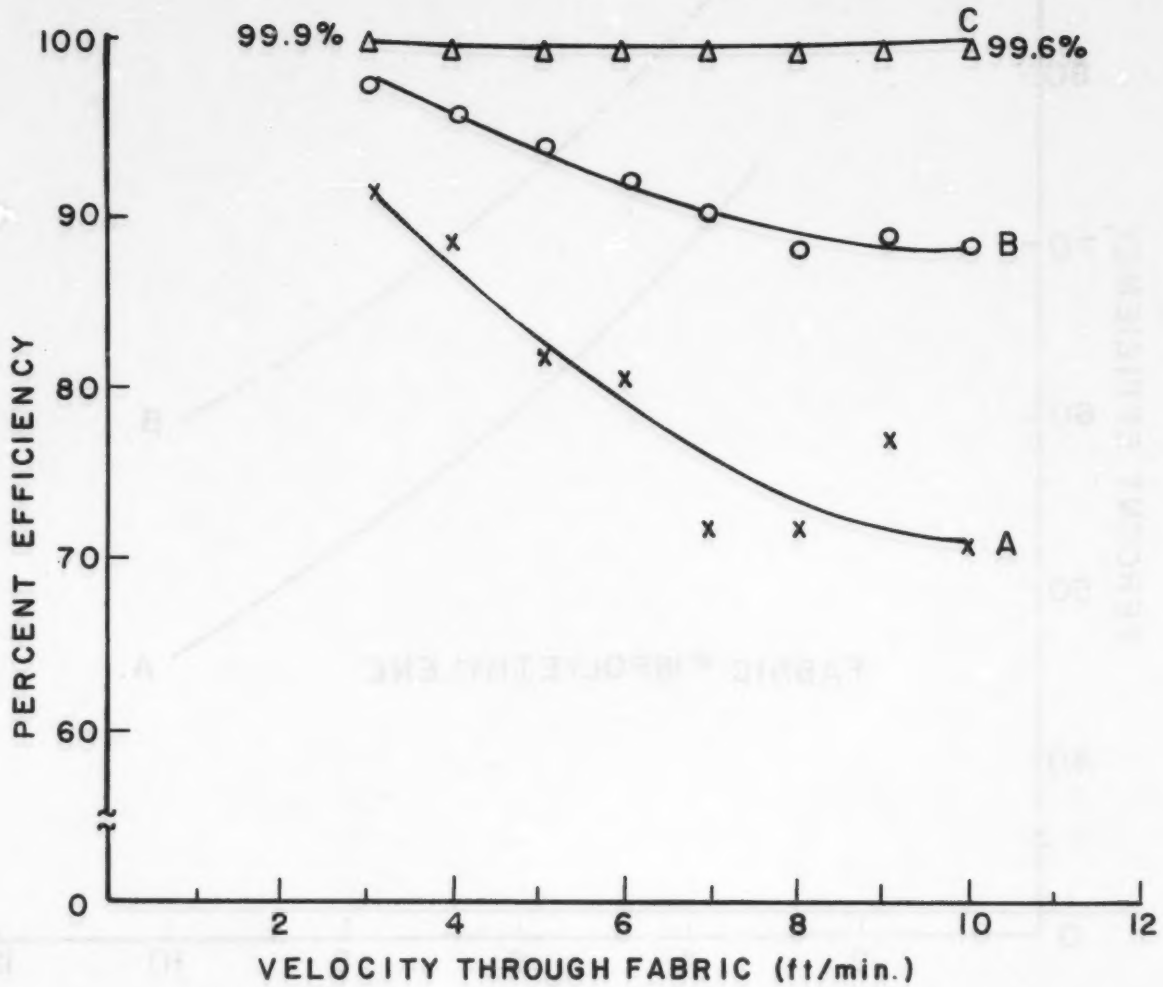


Figure 26 - Electrostatic Augmentation of Efficiency of a Clean Woven Glass Fabric

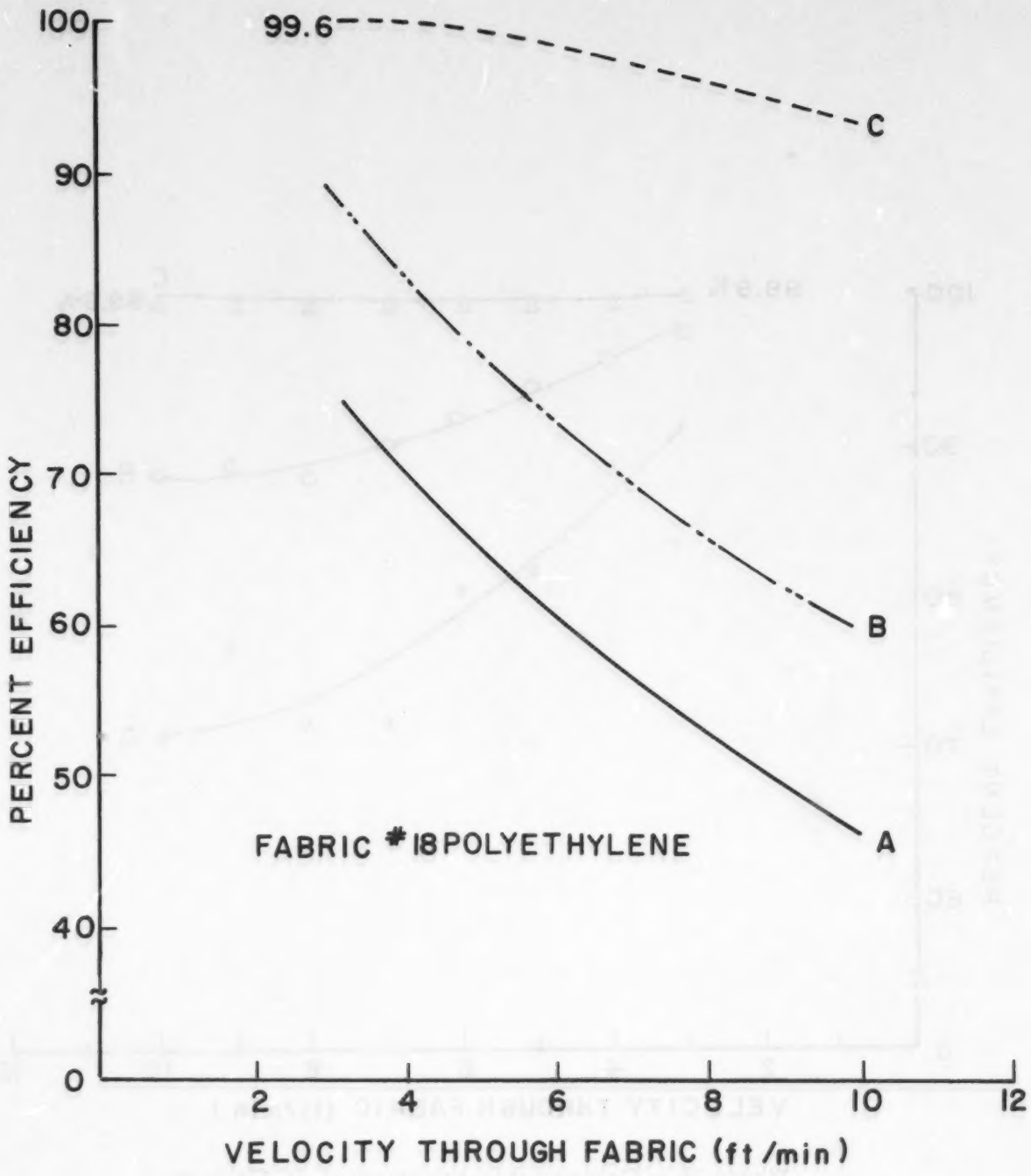


Figure 27 - Electrostatic Augmentation of Efficiency of a Clean Polyethylene Fabric

efficiency is 99.9% at 2 ft/min and 99.6% at 10 ft/min. For all other fabrics the efficiency falls off more rapidly with velocity. The specifications of the various fabrics are given in Volume 2 of this report.

In all cases charging the particles combined with the electric field gave a marked increase in efficiency. In all cases the electric field alone gives some increase in efficiency. It may be that the particles as generated in the arc carry a small charge.

There seemed to be little correlation between efficiency of the clean cloth and the permeability of the cloth.

DISCUSSION

Theoretically the mobility of the fine charged particles should be about 10^{-3} cm^2/volt sec. The electric field perpendicular to the fabric can seldom exceed 5 Kv/cm. Thus the velocity of the particles relative to the air could be of the order of 5 cm/sec or 10 ft/min. Within the fabric local air velocities will be higher than the face velocity and electric fields relatively low. Thus it appears that electric forces should be most effective in capturing particles on the tips of the fibers or nap and this seems to agree with microscopic examination of the dust on the fabric.

The large increase in efficiency of a clean fabric achieved by electrostatic means shows that this is an effect which should be investigated further. The poor correlation between permeability and efficiency for the clean cloth is another area for further study.

SECTION 13

MEASUREMENT OF AGGREGATION OR AGGLOMERATION OF DUST DISLODGED FROM A FILTER

BACKGROUND

In bag filters dust dislodged from a filter must fall downward to the hopper. In a pulse jet system the dislodged dust must fall against upward flowing air. For dust to fall satisfactorily into the hopper it must be dislodged as aggregations or agglomerations and not in the form of the original individual particles. So a test is needed to measure the ability of dust to fall into the hopper when it is dislodged from the bag.

It has been proposed that the agglomeration of dust is accentuated if the dust and fabric are widely different on a triboelectric series. The falling of dust provides a measure of the degree of aggregation or agglomeration of the collected dust.

PURPOSE

The primary purpose of the test was to measure the ability of dust dislodged from the filter to fall against a controlled upward air flow. Other objectives are to measure pressure drops and to compare filter performance with triboelectric properties of dust and fabrics.

APPARATUS

The apparatus utilizes two 4" x 4" filters mounted on opposite sides of a 1" x 4" vertical duct. An adjustable speed fan recirculates the aerosol through this 1" x 4" duct. This vertical velocity can be controlled by adjusting the speed of the fan. Air is drawn off through the filters by another adjustable speed fan. Air from a dust feeder in an amount equal to that drawn off through the filters is injected into the upward air stream below the filters. In this way the air velocity through the filter (air-to-cloth ratio) can be adjusted independently of the upward air velocity past the filter.

In a pulse jet system the upward air velocity varies from top to bottom of the bag and also varies with the design of the baghouse. In this test apparatus, any combination of position and design can be represented since upward air velocity and air-to-cloth ratio can be controlled independently.

The arrangement of the apparatus is shown in Figure 28. There is a settling chamber above the filter, called "Bin A," which collects dust, which is dislodged from the filter and carried upward by the air stream.

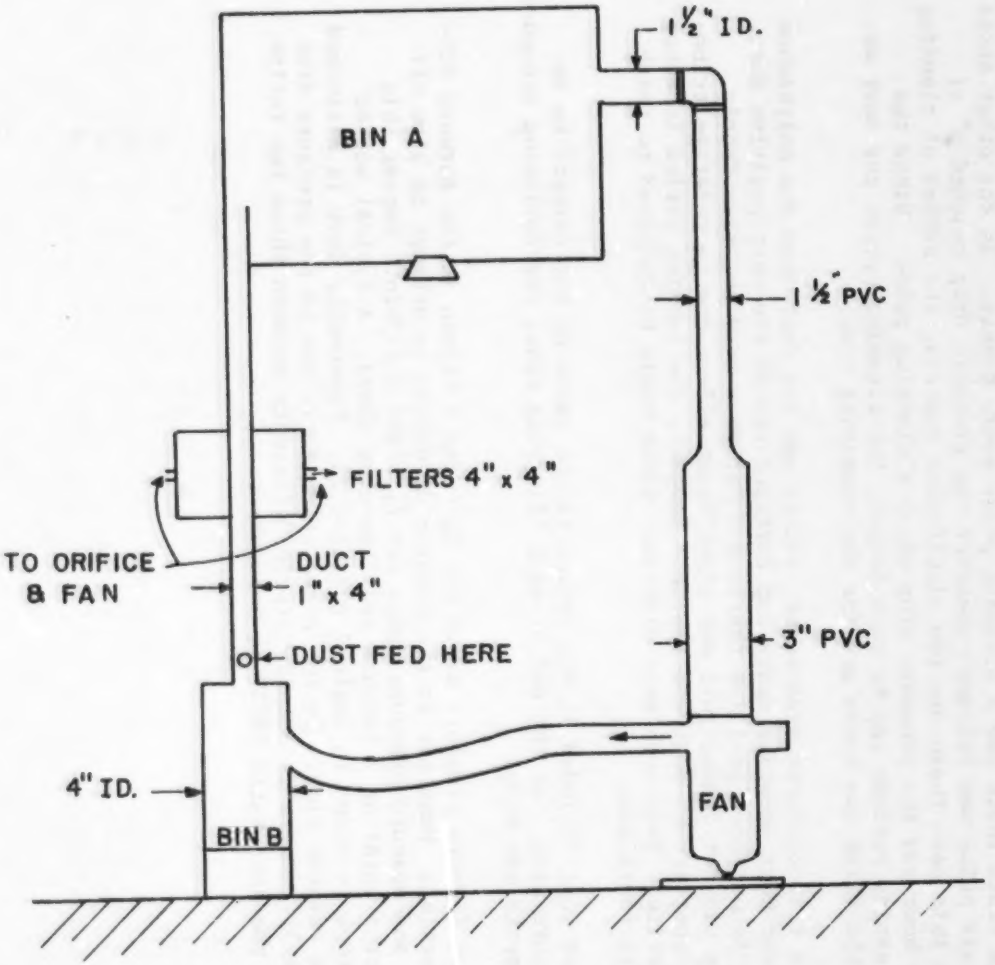


Figure 28 - Apparatus for Measuring Aggregation of Dislodged Dust

There is another settling chamber below the filter called "Bin B." If dust dislodged from the filter is able to fall against the upward air velocity, it will be collected in Bin B.

RESULTS OF TESTS

The upward air velocity was varied from 200 to 600 ft/min. In all cases the filtering velocity (air-to-cloth ratio) was 6 cfm/ft^2. The results are listed in Table 8.

In six tests there was a cleaning pulse every minute. In the other tests a reverse air pulse was released whenever the pressure drop reached 4" of water. In this case there are two significant numbers, the number of cleaning cycles per hour and the pressure drop after a cleaning pulse. Since the initial cleaning periods may be much longer, the cleaning cycles per hour are given for the first two hours and for the remaining time.

From a triboelectric standpoint, silica and the dust from the molybednum plant are our most negative dusts and Portland cement the most positive dust. Wool-nylon is our most positive fabric and Teflon a very negative fabric. These tests did not demonstrate any significant effect due to relative triboelectric properties of dust and fabric. However, the fabrics varied in other characteristics. Thus much more elaborate tests would be required to reach any definite conclusion.

Another test included in the series is the ratio of the forward to reverse pressure drop. At the end of each filtering test, the following sequence of measurements was made.

Measure forward pressure drops for 2, 6 and 8 ft/min in the forward filtering direction. Pass air in the reverse direction to attempt to blow off the filter and measure pressure drops for 2, 6 and 8 ft/min. Repeat this sequence for a total of 3 forward and 3 reverse flows. A typical set of pressure drops is shown in Table 9 for test 26. Presumably dust is dislodged only during reverse flow. So the comparative ratio can be the pressure drop 1R/2F or 2R/3F. There is usually little difference between these two ratios. In Table 9 the last ratio 2R/3F is tabulated.

TABLE 8. FILTERING WITH VARIABLE UPWARD AIR VELOCITY

Test	Upward Air Velocity Ft/Min	Dust	Fabric	Room RH	% Of Dust In Bin B*	Cleaning Cycle HR 0-2 Hr.	Cleaning Cycle HR Remaining Time	Pressure Drop After C.C. "H_2O	Dust Loading Grains ft3	Duration Of Test Hours	Ratio Forward Reverse Air Pressure
16	200	S	WN	14%	56	1	3	.6	-	5.25	1.82
24	240	C	WN	20%	75	45	160	3.4	3.0	4.5	4.5
23	240	C	WI	23%	58	1 C.C. Every Min.		1.5-4.5	2.1	5.0	4.75
25	240	C	T	21%	76	1 C.C. Every Min.		1.0-3.0	3.2	4.0	2.15
26	240	C	T	20%	60	38	59	1.0-3.25	2.0	5.0	2.0
28	240	C	D	21%	67	45	110	1.0-3.5	4.0	5.0	3.1
30	240	C	D	25%	59	21	46	1.0-3.0	3.7	5.0	2.7
29	240	C	D	20%	59	1 C.C. Every Min.		0-3.5	3.25	4.0	2.75
31	240	C	D	33%	48	1 C.C. Every Min.		1.0-3.5	3.4	6.0	2.8
33	240	C	D	18%	60	1 C.C. Every Min.		1.0-5.0	3.5	4.0	3.0
34	240	C	D	50%	78	18		1.0-3.0	3.0	3.5	2.5
36	240	B	D	18%	53	12	25	4.0	1.2	3.75	2.6
37	240	B	DT	20%	45	.5	1	4.0	?	4.0	2.0
20	400	C	WN	15%	73	1.5	2.25	2.0	.2	5.0	3.33
22	400	C	WI	13%	47	1 C.C. Every Min.		1.5-2.5	1.5	5.5	2.13
15	400	S	WN	16%	30	.5	3.2	.8	-	4.5	1.92
18	400	S	WI	20%	37	2.5	5	1.5	.09	4.5	3.9
14	400	S	T	22%	39	2.5	5.3	1.6	-	3.5	1.07
21	600	C	WN	18%	28	3.5	3.6	2.0-2.5	.302	10.0	3.0
38	600	C	D	60%	26	15	25	1.0-2.0	-	4.0	2.1

* Percent of dust that is able to fall against stated upward velocity.

Dust Type
S - Silica
C - Cereal
B - Brown Ferro Moly

Filter Fabric
WI - Wool-Nylon
T - Teflon
D - Dacron
DT - Draylon T

Definitions
C.C. - Cleaning Cycle by Reverse Air Blast

TABLE 9. MEASUREMENT OF FORWARD AND REVERSE PRESSURE DROP: THE CONCLUSION OF TEST #23

Face Velocity $\frac{CFM}{FT^2}$	Pressure Drops (inches of H_2O)					
	1F	1R	2F	2R	3F	3R
2	1.1	.4	.7	.35	.6	.3
6	4.5	.9	3.35	.85	3.1	.8
8	7.4	1.3	6.3	1.25	5.9	1.2

Ratio $2F/1R = \frac{6.3}{1.3} = 4.85$ $3F/2R = \frac{5.9}{1.25} = 4.7$ at 8 ft/min.

F = Air flow in the forward or filtering direction

R = Air flow in the reverse or cleaning direction

SECTION 14

NODULAR DEPOSITS IN FABRIC FILTERS

INTRODUCTION

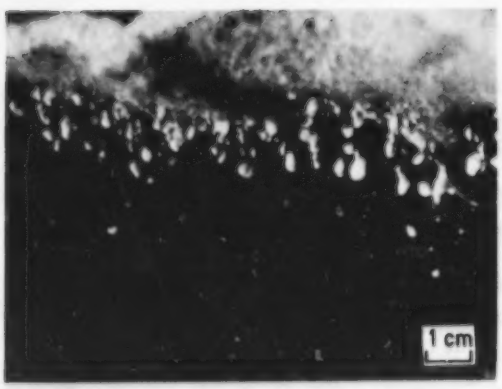
One phenomenon in fabric filtration is the appearance of agglomerations or clumps of dust suspended from one or more fibers. The most obvious examples of these nodules or 'dingleberries' are those which hang away from the filter surface. Two examples are shown in Figure 29. One apparent effect of these deposits is the extra weight added to the fibers that hold them. Without closer inspection, these nodules appear to be just an interesting anomaly. But this discussion will show that deleterious effects can arise if these formations are left on the filter. The persistence of the nodules even after many cleaning cycles relates to their particle size makeup and the mechanical holding action of the fibers. For nodules held close to the surface of the filter, a 'check valve' effect can arise giving a high pressure drop in the filtering direction but low pressure drop in the reverse or cleaning direction. High speed movies show this effect and give a possible clue to the mechanism of formation of nodular deposits.

NODULE COMPOSITION

An important property of nodular deposits is their particle size makeup compared with the particles present in the inlet dust stream. Does the nodule just mirror the inlet dust in terms of particle size distribution? To answer this question, many nodules were examined in the Scanning Electron Microscope (SEM). These nodules were formed during laboratory scale filter tests. Different types of fabrics and cleaning cycles were employed. Two types of dust were used and with both, nodular deposits eventually formed. The first type of dust used was an asphalt plant rock dust composed primarily of silicon, aluminum, and iron. The second type of dust used was silica. Samples of each dust used are given in Figure 30.

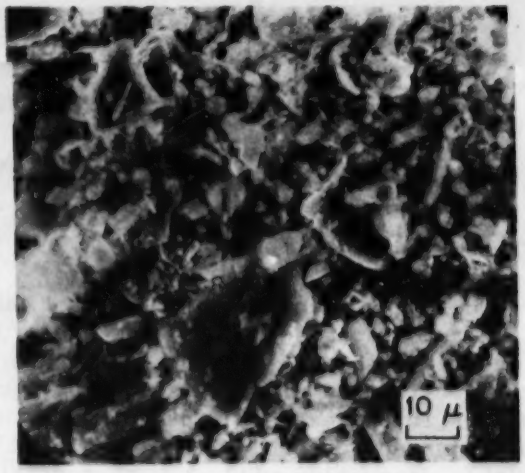
A rock dust nodule that formed on a Nomex felt filter is shown in Figure 31. A view of the individual particles in the nodule is shown below. This nodule was removed from the filter after 46 hours of filtration. The air/cloth ratio was 6 cfm/ft^2 over the entire filtration period. The dust loading was 2.5 grains/ft^3 for the first 22.5 hours, 5 grains/ft^3 for the remainder of the test. The cleaning method used was a reverse pulse of air created by the release of compressed air from a tank through a solenoid valve triggered by a differential pressure switch. It is important to note that the particle size found in the nodule is much smaller than the maximum particle size seen in the rock dust (Figure 30). And although many of the larger particles in the inlet dust stream settle out before reaching the filter surface, the maximum particle size found in the nodule is much smaller than the largest particle

(a)

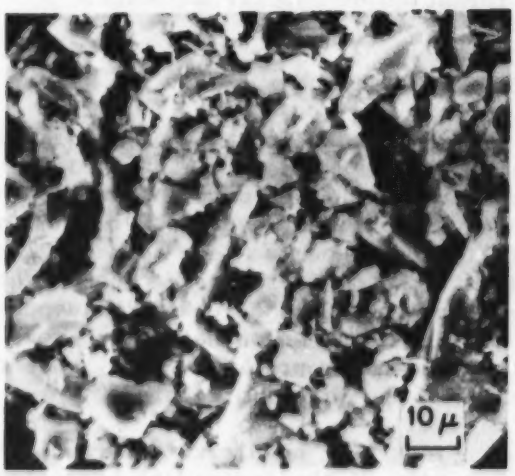


(b)

Fig. 29 - Nodules hanging from fibers: (a) Rock dust, (b) Silica dust.



(a)



(b)

Fig. 30 - Inlet dust particles: (a) Asphalt plant rock dust, (b) Silica dust.

reaching the filter. Many 30-40 micron particles reach the filter but were not found in the nodule.

A silica nodule found on an acrylic fiber after 52 hours of filtration is shown in Figure 32. The individual particles are shown below. The filtration cycle consisted of a dust loading of 3.1 grains/ft^3 at an air/cloth ratio of 6 cfm/ft^2. The fabric used was a 50/50 wool/acrylic felt with a permeability of 130 cfm at 0.5 inches H_2O. The filter was cleaned with a reverse pulse of air when the pressure drop reached approximately 4.5 inches H_2O. The maximum particle size found in the nodule is about 10 microns. Again, as in the first case, only the smaller particles of the inlet dust stream are found in the nodule. This has been typical in every nodule observed even through filtration conditions were modified.

The persistence of these small particle formations even after repeated cleaning cycles is consistent with past studies of dust adhesion. Probst[5] has shown that in an electrically deposited dust layer (dust charged and precipitated), the smaller particles will exhibit a higher adhesive force than the larger particles. Figure 33 shows this relationship for four different dusts. The particles were separated into different sizes, deposited electrically, and the force required to remove the dust layer measured with a vertical centrifuge. A later study by Niedra[6] showed that randomly deposited particles not using an electric field to aid deposition can exhibit adhesion of the same order of magnitude as the electrically deposited sample. In the randomly deposited sample, adhesion again decreased rapidly with increasing particle size. The adhesion of 10 micron silica was 8-15 gm/cm^2, but only 0.5 gm/cm^2 for silica particles in the 37-44 micron range.

While the cleaning cycles remove the less adherent deposit, the very adhesive particles continue to stick to fibers or to each other. As such, nodule formation may be a random process. Of the many particles that touch fibers or other particles, only the adhesive particles remain after the cleaning cycle. It should be noted that the randomly deposited sample allowed each particle to arrive and orient itself prior to touching another particle. The opposite of this would be to pour a quantity of dust onto a metal plate where most of it would slide off easily if the plate were tilted. Nodules are very adherent and the long time required to form the larger nodules suggests this random formation process where certain particles and aggregations of particles remain even after repeated cleaning cycles.

THE MECHANICAL HOLDING ACTION OF FIBERS

The nodules which are easily observable are those which hang away from the fabric surface as in Figure 29. Most of these nodules are held by single

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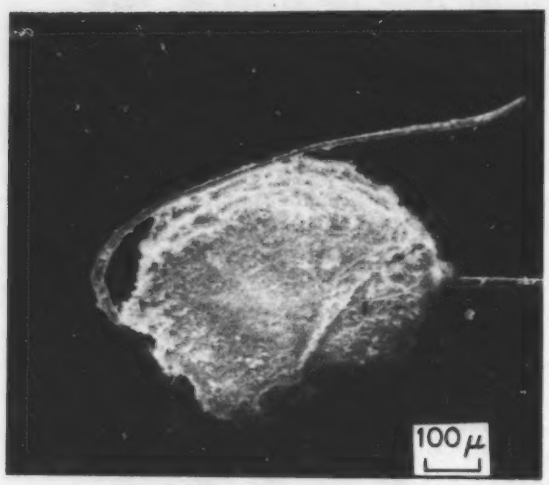
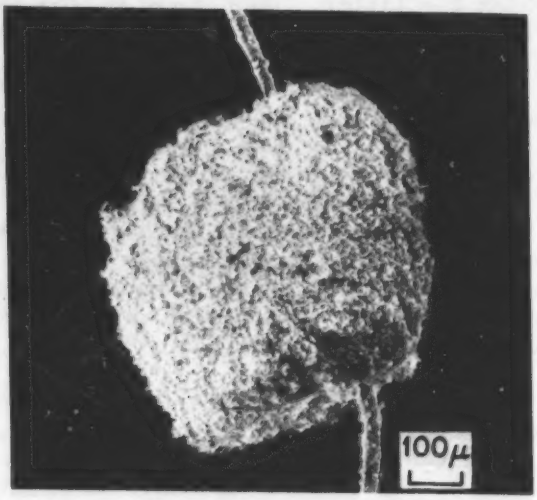
[5]R.E. Probst, "Dipole Phenomena and Particle Size Effects in Electrostatic Precipitation," Ph.D. Thesis, Carnegie Institute of Technology, Pittsburgh, PA (1962).

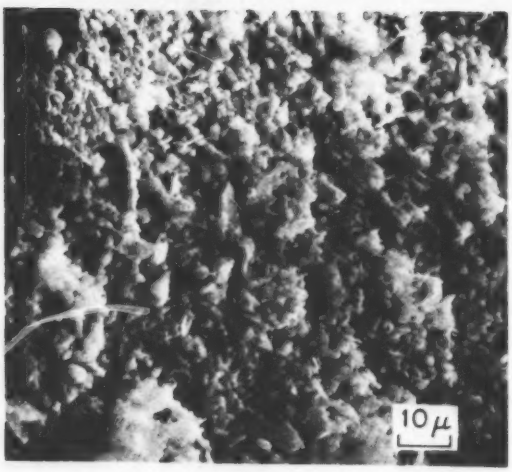
[6]J.M. Niedra, "Electrical Effects in the Adhesion of Powders," Ph.D. Thesis, Carnegie Institute of Technology, Pittsburgh, PA (1964).



(a)

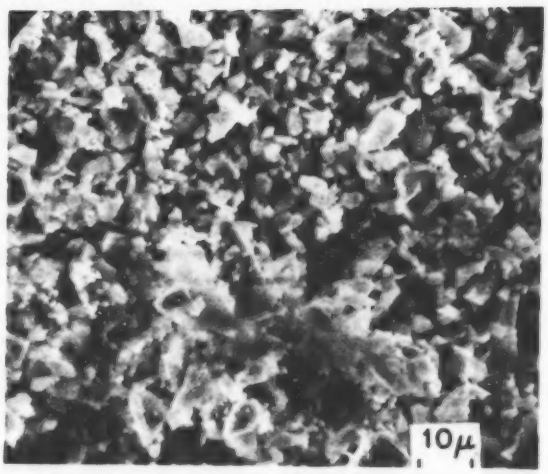


(a)



(b)

Fig. 31 - Rock dust nodule and particle makeup: (a) Nodule and nomex fiber, (b) Particles in the nodule.



(b)

Fig. 32 - Silica dust nodule and particle makeup: (a) Nodule and acrylic fiber, (b) Particles in the nodule.

fibers. The nature of the holding action will be discussed in this section. A direct look at the site of the nodular formations gives a clue to the reason for their ability to hang from the filter surface. The holding of the nodule to the fiber is best described by the geometry of the spot on the fiber where it is located. Nodules can also be held by more than one fiber. This becomes important later in describing the check valve effect. Small nodules, about 10 fiber diameters wide (about 200 microns), are often spherical, indicative of an abrading process whereby the less adherent particles and protruding edges are removed during successive cleaning cycles while the nodule itself remains intact.

Nodules, when observed after a long filtration cycle and many cleaning cycles, are found to encompass kinks or irregularities on the fibers. Several examples are mentioned here. A silica nodule taken from the same filter as the nodule in Figure 32 was examined in the SEM. The acrylic fiber on which it was found entered the nodule at one point but appeared to divert from this path before exiting the nodule. By pressing a pointed object to the nodule, it fractured revealing the underlying structure of the fiber. The fiber had a bend or kink in the area where the nodule once surrounded it. The nodule, when fractured, split into several pieces which fell away from the fiber with little of the original nodule still clinging to the fiber.

A second silica nodule formed on the same type of fiber indicated how an irregularity may accompany a nodule. When viewed in the SEM, a short piece of fiber was found exiting the nodule along with a fiber which appeared to pass directly through the nodule. But, after fracturing the nodule, two separate fibers were found entering the nodule. The short fiber exiting the nodule was the termination of the fiber entering from the filter side of the nodule. The other fiber was not connected to the filter when the nodule was removed from the filter. Another example of a fiber irregularity had the fiber twisted almost 180 degrees at the center of a silica nodule.

Whether these sites are the actual formation areas of the nodules is uncertain since modules have been observed to have the capability of sliding on a fiber, remaining intact. This would explain the appearance of nodules on fibers which are quite a distance from the filter, as in Figure 29. The nodule could slide until stopped mechanically by a kink or irregularity.

The cleaning cycle mentioned previously would also tend to cause nodules to slide away from the filter surface. The air pressure pulse causes the fabric to accelerate outward providing a snap action. Some nodules would continue to remain after the cleaning cycle and would be found hanging relatively far from the fabric as in Figure 29. While the single fiber nodule is common, large nonspherical multiple fiber nodules also appear. The cleaning technique presumably affects the presence or absence of the multiple fiber nodules.

THE CHECK VALVE EFFECT

From an engineering standpoint, the results presented so far do not describe the dynamic filtration effects of nodular deposits. This section will show how nodular deposits exhibit themselves in terms of pressure drop across

a filter. A key observation is the appearance of the check valve effect in filters having these deposits. Comparison of forward and reverse flow measurements and direct observation of the dust cake movement under reverse air flow complete the examination of the valve effect.

The nodules which hang away from the fabric surface as in Figure 29 do not affect the overall pressure drop characteristics of the filter. But the nodules which are close to the fabric surface can influence the forward and reverse pressure drops of the filter. As used here, the forward pressure drop is the pressure drop in the normal filtering direction. The reverse pressure drop is the drop in the cleaning direction. A model of nodule action during the application of forward and reverse air flows is presented in Figure 34.

The best way to observe this type of action is by applying forward and reverse air flows and, while this is occurring, recording the movement of the dust cake with a movie camera. This was accomplished using the rock dust and nomex filter mentioned previously. With the dust cake facing up, both forward and reverse air flow pressure drops were measured at air/cloth ratio between 3 and 11 cfm/ft^2. The plot of pressure vs. air/cloth ratio for these two cases is given in Figure 35. The reverse flow pressure drop is considerably less than the forward flow drop. A sequence of photos made from the vertical and the dust layer is shown with no applied flow. In the second and third photos, a reverse air flow is applied for increasing air/cloth ratios. The last photo is at an air/cloth ratio of approximately 6 cfm/ft^2. The opening of the crack in the center of the pictures is a visual example of the check valve effect. The filter cloth was securely held and its motion under this reverse flow is negligible. While this same type of movement has been documented for the smaller type of nodular deposit previously discussed, this sequence of photos gives the best visual picture of the effect and the analogy to a valve opening and closing under forward and reverse air flows.

The check valve effect, exhibited by differences in forward and reverse pressure drops, can appear soon after filtering begins even though nodules which are large enough to be easily seen may not become apparent until much later. An example of this early presence of the check valve effect is shown in the pressure drop characteristics of Figure 35. This is a time history of forward and reverse pressure drops at various times in a filtration cycle for two fabrics filtering the same dust. The difference in forward and reverse pressure drops is seen at hour 16 and increases considerably by hour 46. By hour 52, the ratio of forward pressure drop to reverse pressure drop is about 5 to 1 even though the reverse pulse cleaning was employed.

A THEORY OF FORMATION

While the effects of nodular deposits have been indicated and examples of nodules presented, the cause of this type of formation is unclear at this time. In this section, evidence will be presented which indicates how such a deposit might form. It would be best to observe one fiber over a filtration period and watch to see if a nodule formed. An easier approach is to observe the break-up of the dust cake during a cleaning pulse. It was stated previously that nodules could slide along a fiber. This tends to indicate lower adhesion

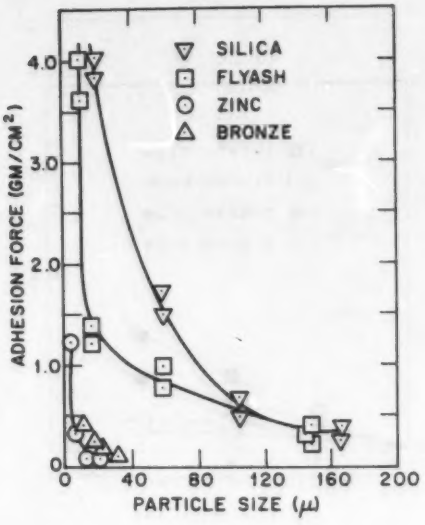


Fig. 33 - Adhesion Force vs. Particle Size for Four Materials

(After Probst[5])

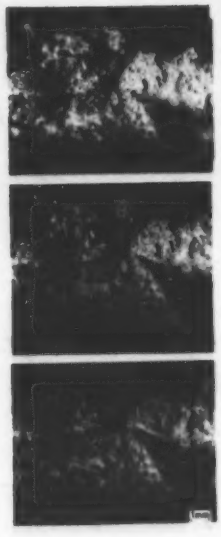


Fig. 36 - Opening of nodules subjected to a reverse air flow. From no flow (top photograph), the air/cloth ratio is increased to about 6 cfm/ft^2 (bottom photograph).

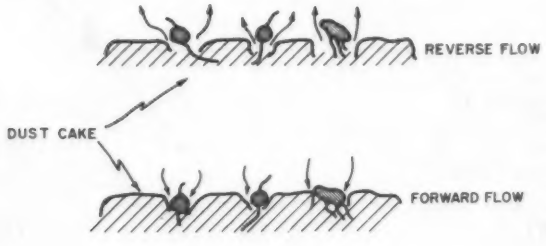


Figure 34 - A Model of Nodule Action

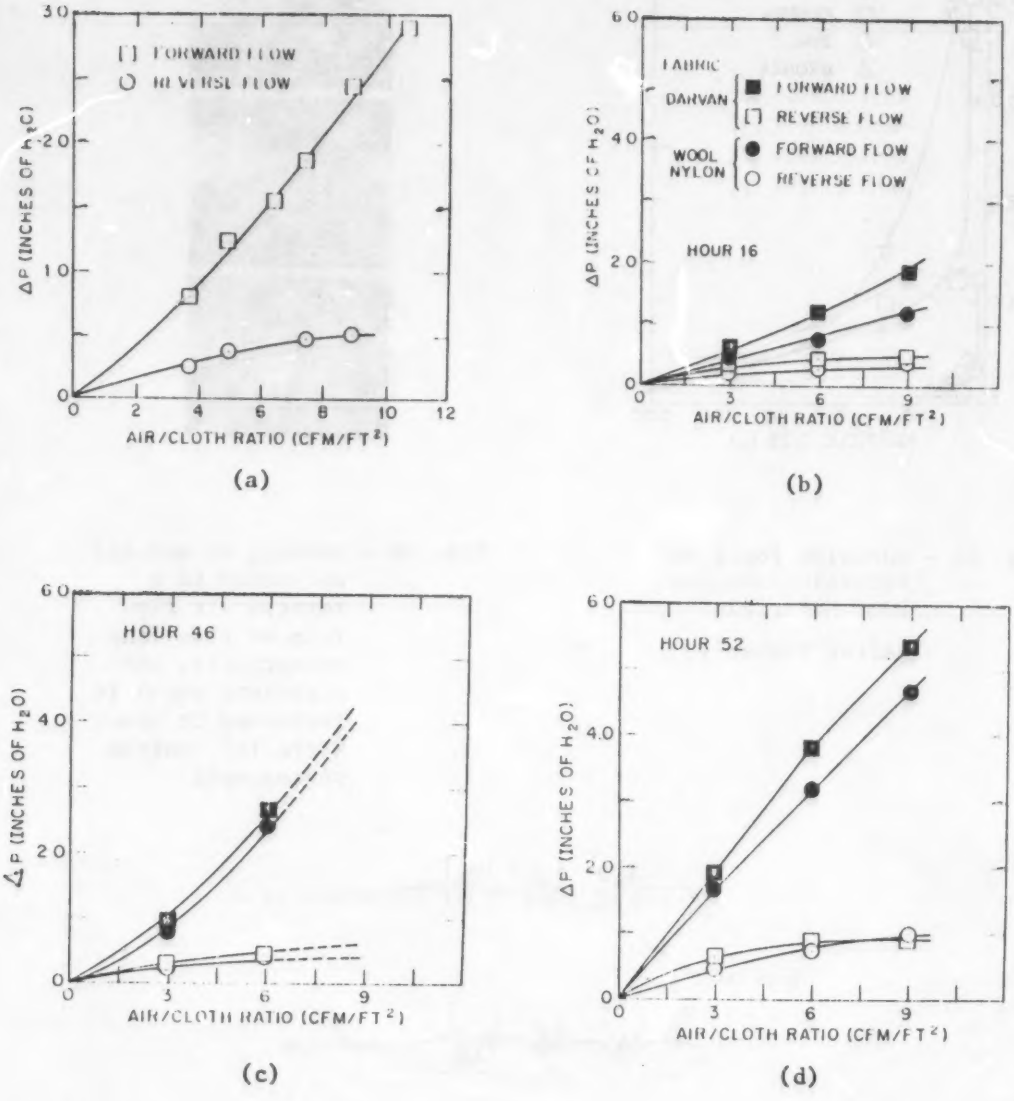


Fig. 35 - Forward/reverse pressure drops of rock dust and nomex felt, (a), and time history of forward/reverse pressure drops for two fabrics, (b, c, and d).

between the particle and fiber than particle to particle in these tests. If this is the case, it would seem reasonable to expect creation of a nodule if a dust layer would fracture while surrounding a fiber leaving a core on which other particles may deposit.

Several dust cake break-ups were investigated to ascertain whether nodule formation could be related to the reverse pulse cleaning technique. One particular example of the effect of a reverse pulse was for a nomex felt filter filtering the rock dust shown in Figure 30. The filtration cycle was the same as that for the nomex felt/rock dust case presented in the first section. The test was stopped after 22.5 hours. A high speed camera recorded the action of the dust cake during the reverse pulse. The time between individual frames was about 1.55 milleseconds which was adequate for observing the dust cake break-up. A particular sequence of frames began just before the pulse arrived and continued until the dust, flying off the filter, obscured everyting.

The high speed moving picture can be described as follows - the first 4 frames (6.2 milliseconds) show the initial effects of the pulse. As the pressure wave struck the filter, the gas was forced through small cracks in the dust cake giving a geyser-like appearance. Then, after 6 milliseconds, as the pressure increased, these areas could no longer release the gas fast enough and the cake fractured. The fractured pieces opened up to release the gas but still remained on the fabric surface which had moved very little up to that point. This opening up of the cake at this stage was very similar to the model for nodule movement under reverse flow given in Figure 34. As the pressure kept increasing, these pieces opened up more in an effort to release the gas. At the end of the photographs, the fabric began to move. This fabric movement can be compared to a test in which a clean filter of the same material received the same cleaning pulse. For the clean filter, the maximum excursion was reached 12.5 milleseconds after arrival of the pressure pulse. The maximum distance travelled by the filter was 13 mm and 85% of this distance was covered between 9.5 and 12.5 milleseconds. So most of the fabric movement occurred in a relatively short time span. Although the movement of the dust laden filter was not measured during the sequence above, comparison to the movement of the filter gives a rough estimate of when the fabric begins to move rapidly neglecting the inertial dust loading. With this approximation, the release of the dust cake from the fabric surface corresponds to the time the fabric begins to move. The photographs show this to be a reasonable assumption.

The two major events seen in the reverse pulse application were 1) the fracturing of the dust cake before removal from the surface which may be an indication of a nodule forming mechanism, and 2) the snap action of the fabric removing the fractured pieces of dust cake from the surface.

CONCLUSIONS

Nodules have been shown to be composed of the small particles of the inlet dust stream. This is consistent with past studies showing small particles exhibiting higher adhesion than large particles. The smaller nodules often encompass kinks or irregularities in the fibers which can provide a

mechanical constraint preventing removal from the fiber. Both small and large multiple fiber nodules evidence themselves by the check valve effect producing a difference in forward and reverse pressure drops at a constant air/cloth ratio. The break-up of the dust cake prior to release from the fabric during a reverse pulse suggests one method by which nodules may form.

SECTION 15

DEMONSTRATION OF ELECTRIC FIELD BETWEEN ADJACENT FIBERS OF A FILTER

INTRODUCTION

A student, Arthur E. Uber III, made tests to explore possible fields between adjacent fibers of a filter. For an aerosol he dissolved food colorings in alchohol. This solution was dispersed into air using a nozzle giving a fine spray. As the alcohol evaporates this left submicron particles of red and blue coloring. An aerosol of one color, e.g., red, could be charged negatively by corona and passed through a filter. Then a blue aerosol could be charged positively and be passed through the same filter. The filter could then be examined under the microscope. With many filters red (negative) and blue (positive) particles tended to deposit on different positions, sometimes different portions of the same fiber. The most striking cases were obtained using a resin-treated gas-mask filter (Hansen filter). A photomicrograph showing three fibers of such a filter in which red particles had been deposited is shown in Figure 37. This is a striking example of particles of one sign continuing to deposit on one location.

DISCUSSION

The work demonstrates the existence of electric fields between adjacent fibers but it raises many questions. To resolve these questions would require a much more extensive investigation.

The conventional explanation for the Hansen filter is that static charges exist on resin surfaces and produce the fields between fibers. Davies[7] points out that any reasonable calculation of life time of a static charge on resin cannot account for the observed life time of the filters. Another possible explanation is that there are contact potentials between adjacent fibers. Many of the phenomena cited to support the static charge theory can also be used to support the contact potential theory. An investigation of the contact potential theory would involve the work function or contact potential of the particulates collected as well as the fibers.

This work was not carried further because these fields between fibers deposit dust within the fabric where it is difficult to remove. We were looking for means for depositing dust on the fabric rather than within fabric. Furthermore the questions to be answered are very involved so that it appears that a major effort would be required to obtain meaningful results. However this does appear to be an important area for basic research.

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[7]C.N. Davies, Air Filtration, Academic Press, New York (1973) p. 108.

Figure 37 - Negatively Charged Particles Attracted to Particular Fibers

ADDENDUM

ELECTRIC FIELDS IN FABRIC FILTERS DUE TO NATURAL FIBER PROPERTIES

by
Robert F. Lembach

Electric fields between adjacent fibers in fabric filters can arise from the retention of static charge or the existence of contact potential differences (CPD's) between fibers. Both depend only upon natural fiber properties eliminating the need for an external voltage source. To retain static charge for long periods of time, a fiber or dust must be highly insulating. The Hansen type filter consisting of highly insulating resin particles implanted in a wool filter is one example. With static charge placed on the resin particles, nonuniform fields are produced in the filter which aid in attracting incoming particles to yield a high efficiency filter. A CPD between adjacent fibers can produce a similar effect. But whereas static charge decays with time, the CPD does not unless the surfaces of the fibers are altered or covered to produce a new surface.

The following sections examine both techniques of producing electric fields in fabric filters to aid collection. The CPD of several fabric materials was measured by two methods. The resistivity of a resin compound was measured to determine the time static charge would remain. Finally, the nature of the particle deposition in the resin type filter was observed.

FABRIC CONTACT POTENTIALS AS MEASURED BY THE KELVIN METHOD

In 1898, Lord Kelvin[8] introduced a technique for measuring CPD's of metals. As an example, when two parallel plates, one zinc and one copper are electrically connected, there exists an attractive force between them. For closely spaced plates, this force increases as the inverse square of the distance separating them. CPD's of metals are typically on the order of 1 volt or less and can be found in reference texts. A change in surface characteristics by polishing or scratching can produce a change in contact potential. As a result, this contact potential is often referred to as the surface potential.

There is a desire to determine if forces arising from CPD's are important in dust collection apparatus, specifically fabric filters where a 1 volt difference over a 10 μm spacing may give a field of 1 kilovolt/cm. It is necessary to know if CPD's exist for commonly used fabrics and dusts. The triboelectric technique of rubbing two materials together, then separating them to

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[8]Kelvin, Lord, "Contact Electricity of Metals," Phil. Mag., 46:82-120 (1898).

find one charged positively, one negatively, indicates the possibility of CPD's existing between fabric filter materials. Two recent papers[9,10] suggest that a direct relationship exists between the CPD and the charge transferred upon contact. But just as metal surface potentials can be altered by polishing or scratching, a technique which did not disturb the fabric surface would be advisable.

The purpose of these tests was to acquire basic information concering contact potentials of dusts and fabrics. Another reason was to see if a triboelectric series, determined by bring two materials in contact and separating them could be manifested by a nondestructive test such as the Kelvin method. The apparatus, similar to that used by Klingler[11], consisted of two electrically connected electrodes (5x5 cm), an oscillating reference and the sample, forming a parallel plate capacitor. A review of this method is described in [12]. Assuming an electrically linear system, the charge q(x) on a plate is related to the contact potential difference V_{cpd} by the capacitance C(x)

$$q(x) = C(x)V_{cpd}$$

The capacitance is only a function of x due to the mechanical constraint on the oscillating electrode. The time varying current i(t) flowing in the circuit is therefore,

$$i(t) = dq/dt = d(C(x)V_{cpd})/dt = C(x)(dV_{cpd}/dt)+V_{cpd}(dC(x)/dx)(dx/dt)$$

Since the contact potential difference is constant,

$$i(t) = V_{cpd}(dC(x)/dx)(dx/dt)$$

For this geometry, and by neglecting fringing fields, the capacitance is related to the separation x between plates, the plate area A, and the permittivity ε as

$$C(x) = \varepsilon A/x$$

Constraining the oscillating electrode as

$$x(t) = x_0 + x_1 \sin\omega t$$

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[9]Davies, D.K., "Charge Generation on Dielectric Surfaces," Brit. J. Appl. Phys. (J. Phys. D.), 2(2):1533-1537 (1969).

[10]Garton, C.G., "Charge Transfer from Metal to Dielectric by Contact Potential," Appl. Phys. (J. Phys. D.), 7:1814-1823 (1974).

[11]Klingler, E.H., "The Adhesion of Dust as Related to Electrostatic Precipitators," Doctoral Dissertation, Carnegie-Mellon University, Pittsburgh, PA (1961).

[12]Surplice, N.A. and R.J. D'Arcy, "A Critique of the Kelvin Method of Measuring Work Functions," Sci. Instr. (J. Phys. E.), 3:477-482 (1970).

where x_0 and x_1 are constants and ω is the radian frequency of oscillation yields the current for the system model to be

$$i(t) = (-V_{cpd}\varepsilon A x_1 \cos\omega t)/(x_0 + x_1 \sin\omega t)^2$$

which was found to be in good agreement with the experimental current waveform. Determining the CPD involves insertion of a series voltage source in the circuit and adjusting the voltage until $i(t) = 0$. At this point the voltage of the external source equals the CPD between the oscillating electrode and sample.

Tests were performed at room temperature and 60-80% RH. The high humidity was necessary due to inherent limitations on allowable sample resistivity. A vacuum deposited gold oscillating electrode was used as the zero volt reference. Table 10 shows CPD's relative to this reference for several dusts and fabrics. In terms of charge transfer between two contacting materials, the material with the higher relative potential tends to acquire electrons and become negatively charged. Of note was the silica dust which tends to charge negatively in impingement tests. It has a high potential consistent with the impingement results. There appeared to be no definitive relationship between fabric samples. However, since typical filter operations operate at a lower RH, a means of testing higher resistivity materials was developed.

TABLE 10. CONTACT POTENTIAL (VOLTS) AT 60-80% RH

Sample	Contact Potential*
Silica dust	+0.18 to -0.27
Cement dust	-0.26 to -0.52
Wool dust	-0.73 to -0.90
60/40 wool/nylon fabric #97	-0.69 to -0.96
85/25 wool/nylon fabric #96	-0.81
Polyester (Dacron) fabric #79	-0.65 to -1.08
Acrylic (Darlan) fabric #125	-0.83 to -1.12

*Contact potential with respect to gold reference (zero volts).

FABRIC CONTACT POTENTIALS AS MEASURED BY THE RADIOACTIVE SOURCE METHOD

The current waveform i(t) derived in the last section assumes that the sample has a conductivity high enough to allow electrical charges to move through it at a rate much faster than the oscillating electrode frequency. This rate is associated with ε/σ, the ratio of sample permittivity to sample conductivity. For example, a sample with a conductivity of 10^{-10} $(\Omega\text{-m})^{-1}$ and relative dielectric constant ε_r of 3($\varepsilon=\varepsilon_r\varepsilon_o$, $\varepsilon_o=8.85\times10^{-12}$ F/m) yields an ε/σ of about 0.3 seconds. To insure instantaneous changes in i(t) with changes in

external voltage, $\varepsilon\omega/\sigma$ should be << 1. To eliminate this frequency dependence, an alternate scheme to measure the CPD was devised.

This technique employed a radioactive source (^{226}Ra, 1.3 μCuries) to ionize air in the space between the reference electrode and sample. The electric field due to the CPD causes ions to move preferentially and this current is again measured by a series ammeter. As before, a series voltage source is adjusted until the current reaches a null to give the CPD.

The purpose of these experiments was to acquire basic information on dust and fabrics at a lower RH. The technique employed an ionizing agent and a fixed reference electrode. The apparatus is the same as in the previous section except that the reference electrode is stationary and the radioactive source is placed near the periphery of the reference electrode.

Table 11 shows results for several fabrics. Where possible, both the Kelvin method and the radioactive source method were used to determine the CPD. The numerical difference between the two methods used was typically less than 100 mV. A range of potentials is listed since typically four samples of each fabric were tested. Where only a small amount of cloth was available, a single sample was used.

TABLE 11. CONTACT POTENTIAL (VOLTS) AT 20-30% RH

Sample	Kelvin Method	Radioactive Source Method
A 2nd gold sample	+0.082 to +0.031	+0.064 to +0.022
Olefin (polyprop) #1		-0.782
Aramid (Nomex) #2		-0.800
Acrylic (Dralon T.) #3		-0.803
Aramid (Nomex) #4		-0.913
Acrylic (Dralon T.) #5		-0.845
Polyester (Kodel) #6		-0.763
Acrylic (Zefran) #7		-0.942
Acylic (Orlon) #8		-0.819
Polyester/Acrylic (50/50 Dacron/Orlon) #9		-0.855
Polyester #19		-0.839
Polyester (Dacron) #20		-0.745
75/25 Wool/Nylon #96	-0.714 to -0.819	-0.767 to -0.850
Aramid/Glass (87/13 Nomex/Glass) #113 singed side	-0.649 to -0.738	-0.719 to -0.822

continued

TABLE 11. (Continued)

Sample	Kelvin Method	Radioactive Source Method
Aramid/Glass (87/13 Nomex/Glass) #113 plain side	-0.573 to -0.720	-0.682 to -0.782
Acrylic (Darlan) #125	-0.635 to -0.741	-0.707 to -0.800

Underlying these tests was the desire to find materials whose CPD was large enough to produce large electric fields (several KV/cm) in a filter composed of these materials. As seen in Table 11, the fabric CPD's were in a narrow range of -0.6 to -0.9 volts relative to the gold reference. Because of this, it would be difficult to predict the charge transferred upon contact of two of these materials. This is consistent with the difficulties encountered in trying to reproduce triboelectric series although certain trends can be observed. Since these tests did not find fabric materials with large differences in average surface potential, they were stopped at this point.

HIGH RESISTIVITY RESIN PARTICLES IN FABRIC FILTERS

The Hansen wool/resin filter has been treated in several publications[13,14]. Operation is believed to be due to the highly insulating properties of the resin particles. Their ability to hold static charge along with the relatively conducting wool fibers would create nonuniform electric fields in the filter to aid deposition of both charged and uncharged particles.

Tests were conducted to measure the resistivity of a commercial zinc resinate compound found in a zinc resinate (ZnR)/wool/acrylic filter which exhibited the presence of electric fields[15]. Resistivity of the powdered ZnR compound was determined by two methods. First, a dust cup was placed in parallel with an electrostatic voltmeter. A voltage source was applied to this parallel combination, then removed. The decay of the voltage with time was recorded. Knowing the meter capacitance, the ZnR resistance was estimated. Given the dust cup geometry, the resistivity was determined. A second method employed a point to plane corona discharge onto a 2 mm thick ZnR deposit. A metal plate connected to an electrometer was brought over the charged dust layer and a voltage measured. The apparatus was calibrated against a plate at a known voltage thereby giving the ratio of measured voltage to the actual voltage at the dust layer surface. Again, the decay of the dust layer voltage was recorded and a resistivity calculated.

[13]Davies, C.N. (1973), p. 171.

[14]Rossano, A.T. and L. Silverman, "Electrostatic Effects in Fiber Filters for Aerosols," Heating and Vent., 51(5):102 (1954).

[15]Penney, G.W. and A.E. Uber, "Collection of Electrically Charged Par ticles in Filters," J. APCA, 26(1):58 (1976).

Resistivity of the ZnR powder ranged from 10^{16}-10^{19} Ω-cm when measured over a one week period at about 25% RH. Assuming a relative dielectric constant of 3, the relaxation time for static charges would be roughly 1 hour to 30 days.

The next tests examined three filters, a ZnR/wool/acrylic, a wool/acrylic, and a ZnR/stainless steel filter under similar filtration conditions. The last filter was created from a stainless steel filter dipped in a ZnR solution and allowed to dry. Flexing the coated fibers fractured the ZnR coating to produce fibers partially covered with ZnR crystals much like the commercial ZnR/wool/acrylic filter.

Small red particles, typically 0.3 μm diameter when viewed with a scanning electron microscope, were generated by spraying a solution of these particles dissolved in a solvent and allowing the solvent to evaporate prior to entry into the filters. An observable deposit was formed in typically 8-10 hours at a filtration velocity of 6 ft/min. Particles were charged negatively by corona before entering the filter under test.

The appearance of the deposits was similar in the ZnR/wool/acrylic and ZnR/stainless steel filters and resembled a recent APCA cover picture[16]. In the ZnR/stainless steel filter, tree-like deposits grew out from the fibers. Few particles resided on the ZnR particles themselves indicating the presence of a repelling negative charge. No similar type of deposit was discovered in the wool/acrylic filter without ZnR treatment when run continuously for 24 hours.

Since several time constants are generally required to completely discharge a sample, the ZnR would require, assuming the 10^{19} Ω-cm resistivity, almost 5 months time. It appears as if this resistivity is high enough to produce the long lasting high efficiency seen in this type of filter. Davies[17] cites a resistivity of 10^{21} Ω-cm for the best resin compounds which could explain some of the long lasting effects of the Hansen type filter. Evidence of internal electric fields was discovered in both the ZnR/wool/acrylic and ZnR/stainless steel filter. In the latter case, negatively charged particles deposited on the conducting fibers and not on the ZnR particles themselves. If the ZnR particles can be charged negatively triboelectrically as is done to renew the filter, it may indicate a material with a high relative surface potential along with its high resistivity. This additional property could explain Davies' remark that the Hansen type filter performs efficiently much longer than expected (i.e., > 2 years). It is longer than expected since static charges are presumed to have discharged long before that time.

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[16]Penney and Uber (1976).

[17]Davies, C.N. (1973), p. 171.

SECTION 16

CONCLUSIONS TO VOLUME I

1. Aerosol particles striking a surface usually acquire a frictional charge. Often the polarity of the charge is erratic. For silica particles striking a tungsten carbide surface 90 to 100% were charged negatively.

2. Field effects produced by frictionally charged particles can influence the nature of the filter cake.

3. Corona charging of the dust can be used to produce a more porous dust deposit than is produced by uncharged dust. The reduction in pressure drop can be quite significant. However it is not yet commercially feasible.

4. The collection efficiency of clean fabric filters can be materially increased by electrostatic effects.

5. The size of aggregations of dust formed during filter cleaning vary with type of dust, manner of deposition, type of fabric, and relative humidity.

6. Dust collected on a filter may form nodules attached to individual fibers. These nodules may act as "check valves" during forward air flow, but provide low resistance to reverse air flow. In these nodules, the interparticle adhesion may be sufficient so that these nodules are not removed in normal cleaning cycles.

7. Electric fields may exist between adjacent fibers of a filter.